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GUIDE-LINES FOR EVALUATING THE
ENVIRONMENTAL EFFECTS OF UNDERWATER
EXPLOSION TESTS

By
George A. Young

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NAVAL ORDNANCE LABORATORY, WHITE OAK, SILVER SPRING, MARYLAND

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Prepared by:
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ABSTRACT: The environmental effects of conventional underwater explosions are described and quantitative estimates provided where possible. These effects include noise, the deposit of chemical products in the sea and atmosphere, cratering and other bottom disturbances, and the killing of fish and other sea life. The long term effects on the environment are minimal. Nevertheless, knowledge of these is needed to avoid unnecessary harm and to fulfill legal and administrative requirements, including the preparation of Environmental Impact Statements. Also, explosion effects knowledge can be utilized during the planning stages to avert unnecessary delays or interference with essential military test programs.

EXPLOSIONS RESEARCH DEPARTMENT
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WHITE OAK, SILVER SPRING, MARYLAND

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Guide-Lines for Evaluating the Environmental Effects of Underwater Explosion Tests

It is essential that the Navy continue to test the underwater effectiveness of new explosives and of weapons. However, in addition to the various administrative procedures established in the past for the conduct of test programs, a legal requirement now exists to assess the probable environmental impact of any such proposed activity during the planning stage. This report has been prepared to summarize information useful for evaluating the environmental and ecological consequences of underwater explosion tests and to provide guidance for the planning of such tests with minimal adverse effect.

It should be stressed that there is not always a clear distinction between a possibly undesirable effect on the environment and an effect that is immediately hazardous to personnel conducting an underwater explosion field test. This report is not directed toward the problems of safety in explosion testing and should not be used for that purpose.

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Captain, USN
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By direction

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I

GENERAL REQUIREMENTS FOR TESTING

1.1 INTRODUCTION

Underwater explosion testing for military purposes generally falls within the following categories: (a) testing of new explosives, (b) phenomenology studies, and (c) the measurement of damage to a target. In all three cases, the tests may be concerned directly with conventional explosives and weapons or with the modeling of nuclear explosion effects by the use of chemical explosives. Explosive weights range from one pound to many tons; but, for underwater testing in deep water, a weight of ten tons is a practical upper limit.

In most cases, the tests are conducted in ocean areas or in seas that are open to the public and are used for recreational purposes and for fishing. They are therefore highly visible and are subject to public scrutiny and criticism. Most of the complaints that have been recorded are in regard to possible effects on commercial or game fish, although other environmental effects occur that could be considered objectionable. The majority of people with expert knowledge of underwater explosion phenomena believe that the effects of any test on the environment are localized and short-lived and cause no irreversible changes in the general ecology of a natural body of water. Longer-range effects are minimal and can be estimated on the basis of existing information, but these estimates are qualitative because most of the previous work has been directed toward the prediction of the early-time, close-in phenomena of military interest.

The aspect of this problem of major concern to the Navy at the present time is not the direct effect of explosions on the environment, but the lack of knowledge of the facts by the public and by many government officials. Because of the heightened concern about environmental effects during the 1970's, a tendency exists to be overly critical about projects that conceivably have undesirable effects. Certain major technological developments have been halted or delayed by environmental arguments during recent years; for example, the SST, the Alaskan Pipeline, and many nuclear power plants. The burden of proof is placed on the builder or developer, who is forced, in many cases, to develop quantitative predictions on the basis of extremely limited knowledge. In the case of underwater explosions, too, certain programs have been delayed or cancelled; and a need exists to assemble a body of factual information regarding known or potential environmental effects in order to avert the possibility of future curtailment of activities.

The purpose of this report is to summarize the existing relevant phenomenological information, to document the efforts currently in progress to avoid or minimize harmful environmental effects, to summarize administrative and policy guide-lines, and to recommend future procedures. Pertinent case-histories will be cited. The recommendations will apply not only to large-scale testing, but to possible ways of increasing current knowledge of effects on the environment.

Certain alternatives are available to the conduct of large-scale tests in the open sea or in areas such as the Chesapeake Bay that are heavily used for recreational and other purposes. These include the use of saline lakes such as the Great Salt Lake and Mono Lake; the use of a lake or beach on a military reservation; the use of an artificial pond or a quarry; or the use of water that is highly polluted. Small-scale model tests in a laboratory facility are also useful in some cases. Each approach has favorable and undesirable features; these are listed in Appendix C.

1.2 ENVIRONMENTAL REQUIREMENTS

1.2.1 Weather. The primary weather requirement for explosive testing at sea is a low wind speed. This is not simply because of the wind alone, but because of the roughening of the sea surface that accompanies it. A convenient way to estimate this effect is to utilize the Beaufort Scale, which has been used to classify wind effects at sea since early in the nineteenth century. As a result of long experience, tables have been prepared listing the nature of the surface waves, and other effects of the wind, over the entire range of speeds expected to occur in a maritime environment. The lower wind speed portion of the Beaufort Scale is presented in Table 1.1. In addition, a set of definitions of the sea state has been developed independently of the Beaufort Scale. The boundaries of these do not coincide, but average values of the sea state code are included in the table for guidance.

It is obvious that explosive tests cannot be conducted at a Beaufort number of 6 or more. Whether operations can proceed at lower wind speeds depends on the nature of the tests. If all operations are conducted from ships, it may be possible to work in relatively rough water; however, if boats, rafts, or floats must be launched and maneuvered or towed at sea, difficulties will be encountered. Some problems will occur at a Beaufort number of 3; and as a general rule, a Beaufort number of 4 is an upper limit for the use of small boats at sea for explosive testing. At these wind speeds, white caps are frequent and the surface becomes rough and turbulent.

The lower end of the Beaufort Scale shown in Table 1.1 is useful as a guide for any large body of water. It has less validity in a river; and in this case, currents may be more important. Local conditions should be studied prior to the planning of explosion tests in a river, as these can vary considerably within a distance of a few miles.

The reasons for the desirability of smooth water are the following: personnel can work faster and more safely; explosives and gages remain stationary; support cables hang in a straight line; near-surface explosion phenomena are better defined; the data are more reliable and exhibit less scatter; and personnel are less likely to become sick.

Ideally, all tests should be conducted in calm water, but this is impossible because such a condition rarely occurs for more than a few hours at sea. However, statistics on wind-speed frequencies can sometimes be utilized to select firing sites where the probability of hampering wind speeds is low. Unfortunately, these statistics generally omit an important factor, the diurnal variation of the wind. For example, if calm periods consistently occur only during the hours of darkness, a site may be of little value for explosion testing. In addition, wind statistics

TABLE 1.1
BEAUFORT SCALE AND SEA STATE CODE

Beaufort Number	Nomenclature	Wind Speed (knots)	Description of Sea	Average Sea State
0	Calm	0 - 1	Sea like a mirror.	1
1	Light Air	1 - 3	Ripples with the appearance of scales are formed, but without foam crests.	1
2	Slight Breeze	4 - 6	Small wavelets, still short but more pronounced; crests have a glassy appearance and do not break.	1
3	Gentle Breeze	7 - 10	Large wavelets. Crests begin to break. Foam of glassy appearance. Perhaps scattered whitecaps.	2
4	Moderate Breeze	11 - 16	Small waves, becoming longer; fairly frequent whitecaps.	3
5	Fresh Breeze	17 - 21	Moderate waves, taking a more pronounced moderately long form; many whitecaps are formed. (Chance of some spray.)	4
6	Strong Breeze	22 - 27	Large waves begin to form; the white foam crests are more extensive everywhere. (Probably some spray.)	5
7	Moderate Gale	28 - 33	Sea heaps up and white foam from breaking waves begins to blow in streaks along the direction of the wind.	6

Source: Haynes, 1947

from offshore positions are not always available. On a practical basis, it is often more useful to consult local fishermen or boat operators when planning a test, rather than to utilize limited meteorological data. In any event, daily weather forecasts should be obtained during the conduct of an experimental program to obtain advance warning of frontal passages or storms.

Tests can be conducted in light rain, although this is undesirable from a safety standpoint. Explosion tests should not be conducted in a thunderstorm.

1.2.2 Oceanography. A study of oceanographic factors is essential prior to the selection of a test site. In particular, it is important to avoid regions of rough water. Local wind conditions are not sufficient for a decision, as long swells can travel hundreds of miles from a storm at sea and can subsequently appear in regions where the air is calm. It is a good practice to utilize the National Weather Service forecasts of waves and sea state on a daily basis, as well as the weather forecasts.

Special problems may arise in an area such as the Gulf of Mexico, where surface roughness may persist over a broad area for some time after the passage of a hurricane or other type of weather disturbance. It is essential, also, to avoid currents such as the Yucatan Current and Florida Current (Nowlin, 1971).

The Gulf Stream can be particularly troublesome along the Atlantic Coast because it achieves speeds up to 3 knots and it does not remain in a fixed location (Fuglister, 1963). Currents are also a problem in estuaries and at their mouths.

1.2.3 Water Depth. If a test is conducted for the study of explosion effects in water up to 10 feet deep, a location in a lake, pond, or sheltered harbor is more suitable than a firing site on an exposed coast line. In the latter case, the actual depth may vary considerably as a result of tidal action, and the wave problem may be more severe than at sea. However, an offshore shallow site may be advantageous if water depths up to 100 feet are needed.

In such shallow water, it is generally possible to anchor test equipment to the bottom and to achieve better accuracy in the placement of explosives and gages. In some cases, it may be possible to utilize an offshore platform as a base, for example the platforms in the Gulf of Mexico near Panama City, Florida. Stage 1 is 11 miles offshore in water 95 feet deep, and Stage 2 is 1.6 miles offshore where the water depth is 60 feet (Tolbert and Austin, 1959).* It should be noted that extensive areas of relatively shallow water exist in the Gulf of Mexico; however, because of the presence of escarpments, deep water may often be found within a few miles of a relatively shallow test site (Ewing, et al, 1960).

* It was learned recently that these platforms have become havens for game fish, consequently, explosive testing in their proximity may not be permitted.

II

EXPLOSION EFFECTS

2.1 NOISE

The propagation of noise is an undesirable feature in extensive explosion test programs because it is an annoyance to the community. No potential physiological hazard exists, as in the case of the high-level continuous noise generated by many manufacturing activities, or by proximity to gunfire or aircraft; however, noise in itself is considered to be a form of pollution and an invasion of personal rights. The problem is of no concern in tests at sea, but it can be important in inland waters when explosions are relatively shallow and residential areas are within a few miles of the firing site.

The level of explosion sound heard at a distance is strongly dependent upon atmospheric conditions. For example, sound was audible at a distance of 400 miles from a land explosion of 5000 kilograms in Europe during 1925, while locations closer to the source reported no sound (Gutenberg, 1951). Such anomalies had been reported previously in regard to the audibility of gunfire.

The reason for the occasionally distant propagation of sound waves is the refraction of sound in the atmosphere. In the case of large explosions and nuclear tests, refraction occurs in the stratosphere; but when small explosions occur, the sound may be channeled by refraction in a shallow surface duct. In this case, the intensity decreases slowly with distance and zones of exceptional audibility may occur. On rare occasions, this effect could cause window breakage.

It is essential, therefore, to avoid firing on days when the atmospheric temperature near the ground either increases with height or is constant. This type of condition can be presumed always to accompany a fog. It is common during the early morning hours, particularly in the absence of wind.

Reed (1964) has provided some useful criteria, based on experience at the Nevada Test Site. He has stated that large windows may be broken by explosion shock waves with a 0.03 psi overpressure and that sonic booms may break windows at an overpressure of 0.015 psi. Reed also stated that noise may be startling at 0.002 psi.

In the case of underwater testing, the most noise would be generated by an explosion just beneath the surface. The air blast phenomena are complex, but only maximum pressure values are needed for purposes of estimation. Figure 2.1 shows air blast peak pressure as a function of distance for relatively shallow explosions. The highest values may occur at a reduced depth, $d/W^{1/3}$, of 0.20 $ft/lb^{1/3}$ *. The curves represent HBX-1 values, as the best available data are

* Cube root scaling is used in studies of shock wave effects. In this case, all depths and other space dimensions are reduced by dividing by the cube root of the charge weight.

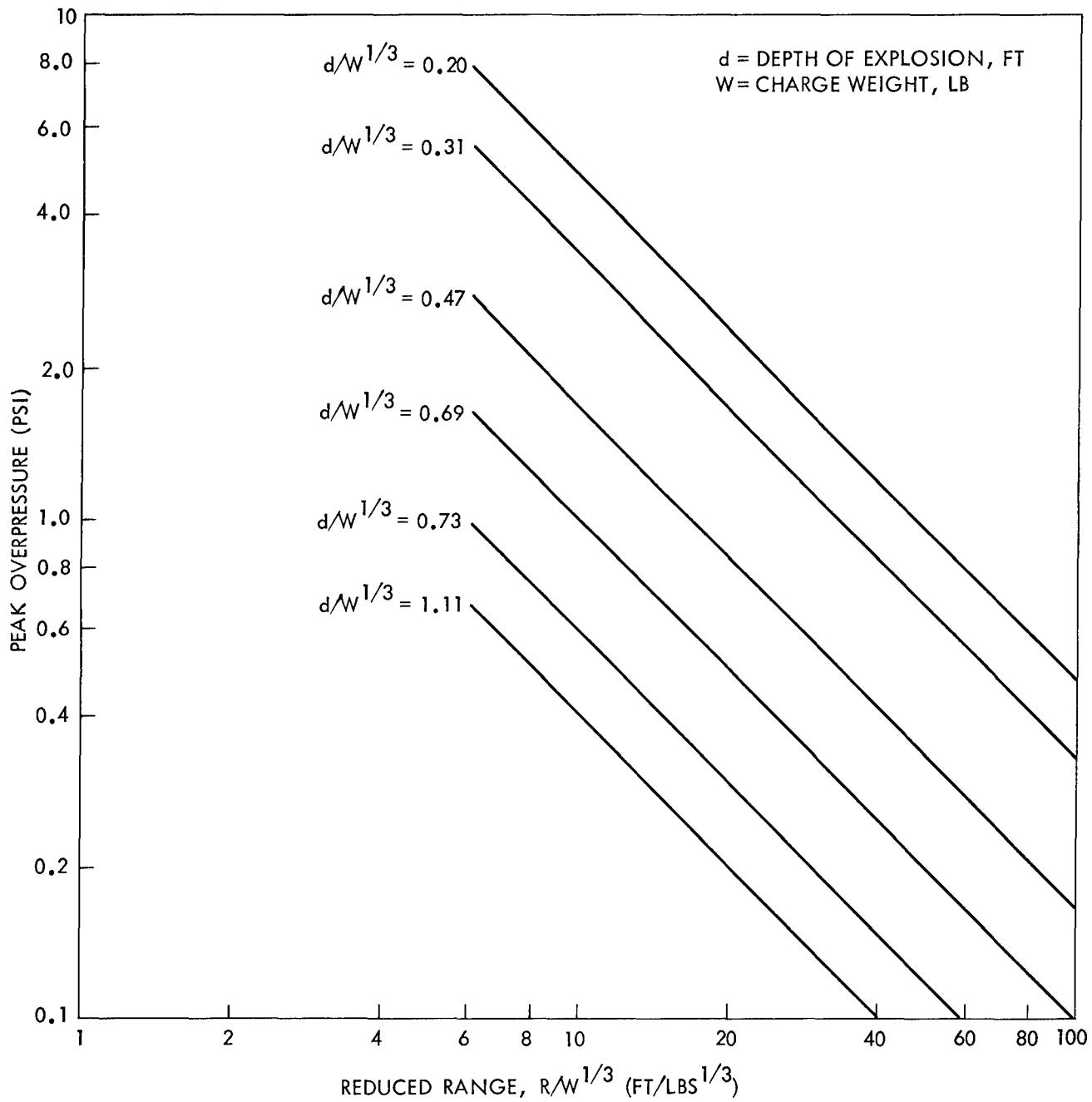


FIG. 2.1 AIR BLAST PRESSURES FROM UNDERWATER HBX-1 EXPLOSIONS

from this explosive. The ranges are slightly larger than would be expected for TNT, but the actual difference should not exceed 10 percent.

The curve for the shallowest depth has been extrapolated to greater ranges for several charge weights in Figure 2.2 to provide some guidance concerning the distances at which sound may be audible. As indicated in the figure, it has been assumed that the threshold of possible slight damage occurs at 0.01 psi and that sound is audible at all pressures above 0.001 psi. Approximate sound levels in decibels are included in the figure.

The following equation may be used to estimate the maximum range of audibility for underwater explosions:

$$R_a = 7.9 W^{1/3} \quad , \quad (2.1)$$

where:

R_a = range of audibility, nautical miles ,

W = charge weight, lb .

Figure 2.2 and Equation 2.1 are valid only in good weather in the absence of wind and low level temperature inversions in the atmosphere. Deeper explosions represent less of a problem, and it is probably reasonable to disregard noise considerations if explosions are at a reduced depth of $2.0 \text{ ft/lb}^{1/3}$ or at greater depths.

2.2 THERMAL EFFECTS

The heating of water by conventional underwater explosions was discussed thoroughly by Young (1971). It was shown that any appreciable heating that might occur would be limited to a relatively thin shell surrounding the explosive charge for a period of only milliseconds after the time of detonation. The rapid turbulent mixing that occurs subsequently will soon reduce any temperature excess to a negligible amount, e.g., with 15-lb charges; this takes place in about two minutes. Figure 2.3 provides an example of temperature records obtained after a Pentolite explosion with this charge weight. Even with a weight of 10,000 pounds, it is doubtful that any temperature anomaly could be detected in the water after a period of one-half hour.

This result should be equally valid in regard to atmospheric heating by very shallow and by surface bursts.

2.3 CHEMICAL POLLUTION

2.3.1 Explosion Products. In this section, only the chemical products of a bare explosive charge will be discussed. If a mine or torpedo is detonated, fragments of metal will doubtless be deposited on the bottom*, and traces of materials from the case and the fusing mechanism may gradually go into solution. The latter is doubtless an effect of minor significance.

The explosives most commonly used underwater are organic nitrated compounds with a chemical formula of the type (C-H-N-O), such as TNT, Tetryl, RDX, and PETN (Cole, 1948). The products of these explosives are probably better known than the products of newer explosives containing aluminum, nitrates, perchlorates, and other substances.

* If an explosive is less than 15 charge radii deep, the fragments may cover a considerable area.

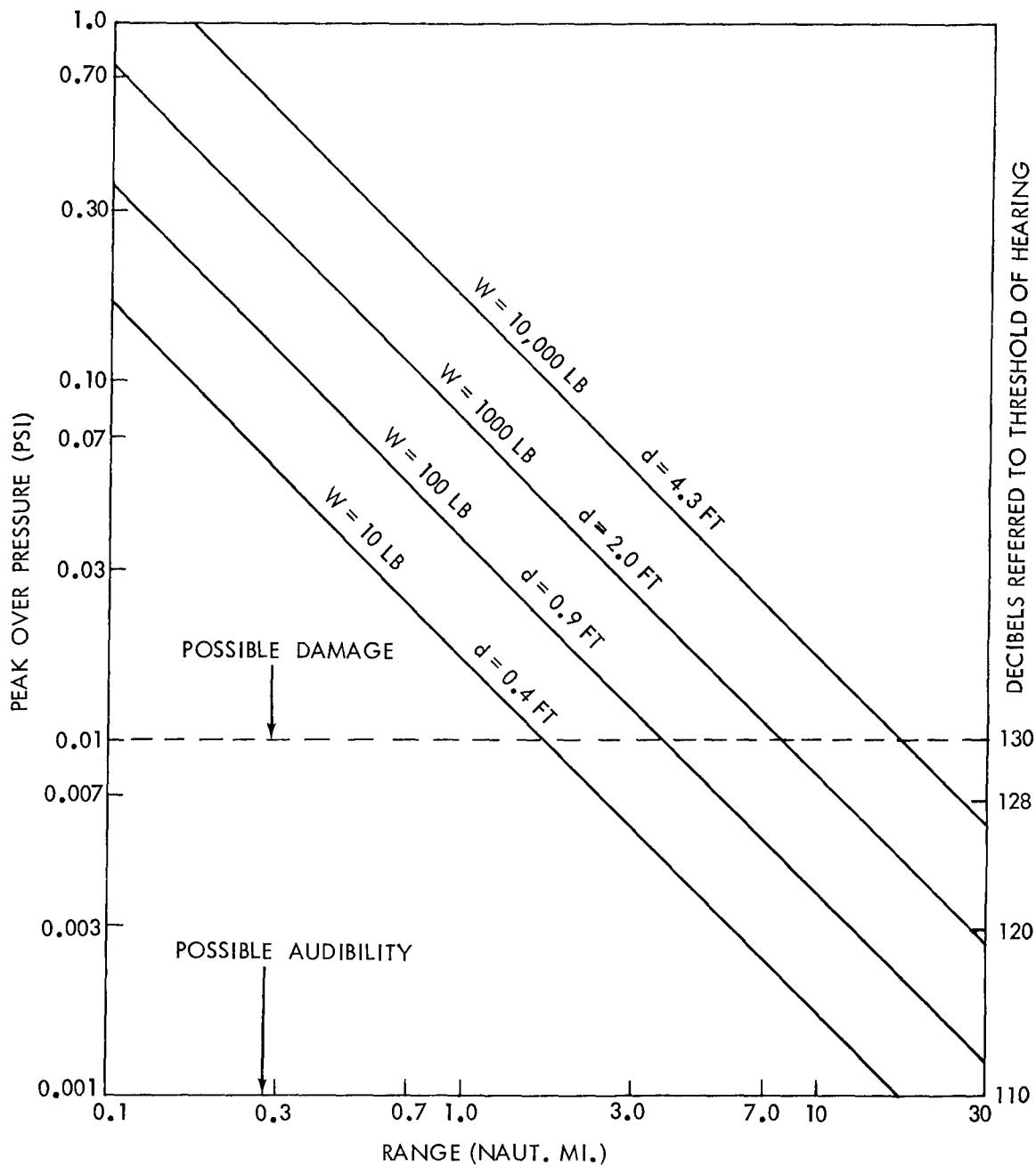


FIG. 2.2 RANGES OF AUDIBILITY FOR SHALLOW UNDERWATER EXPLOSIONS

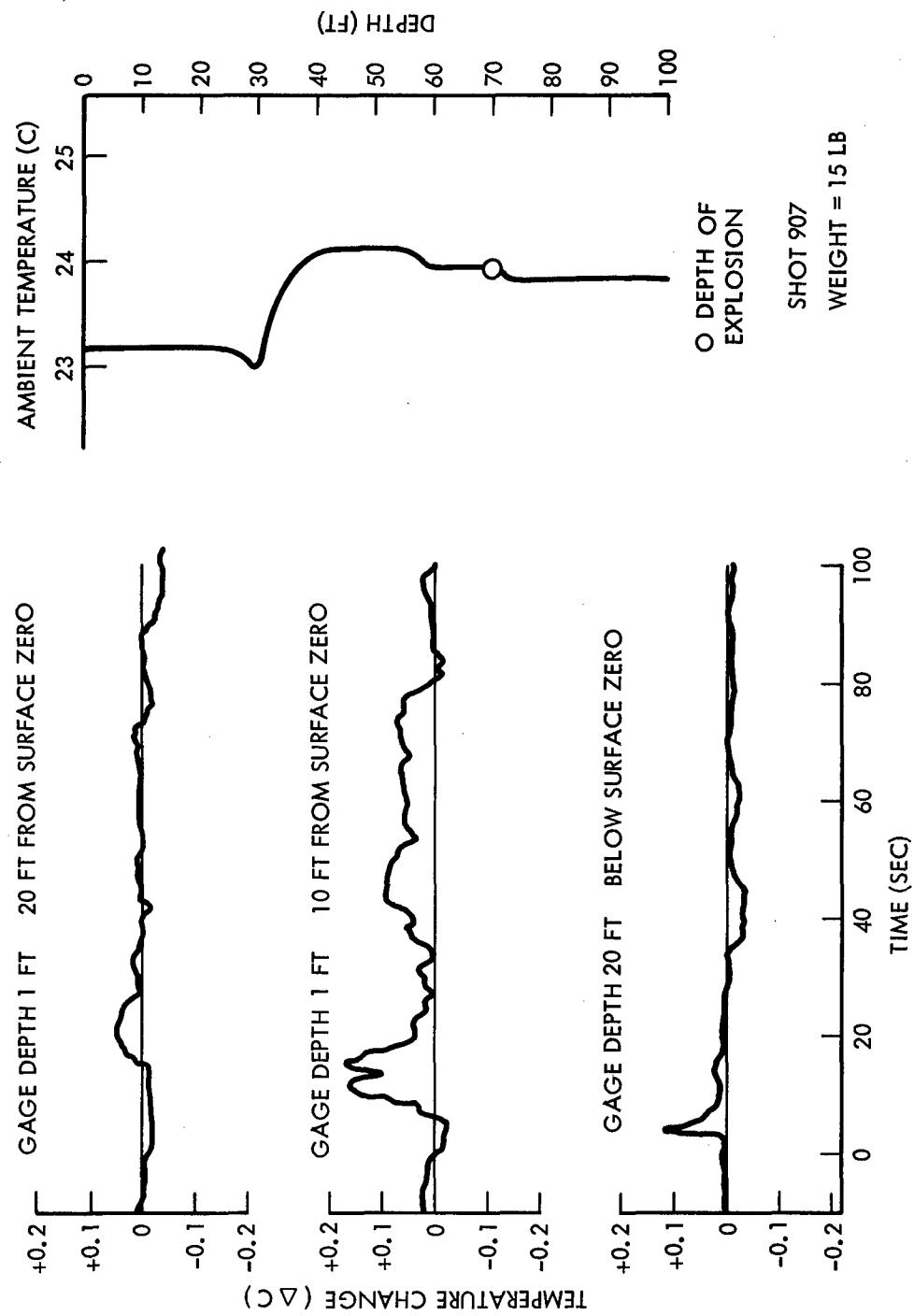


FIG. 2.3 TEMPERATURE CHANGES PRODUCED BY A PENTOLITE EXPLOSION IN FREE WATER

Ornellas, et al, (1966) and Ornellas (1968) investigated the products of detonation of PETN ($C_5H_8N_4O_{12}$), TNT ($C_7H_5N_3O_6$), HMX ($C_4H_8N_8O_8$), NM (CH_3NO_2), and FEFO ($C_5H_6N_4F_2O_{10}$). As the latter two are not used in Navy programs, they will not be considered here. Ornellas analyzed the products of the explosives in a calorimeter and compared the results with calculations based on different theoretical approaches for confined and unconfined charges. The products are listed in Table 2.1A as given in his publications. It should be noted that the C-H-N-O compositions utilized were selected to provide a wide range of oxygen balance, therefore, the quantities of products listed represent the range of amounts to be expected from this type of explosive. In brief, an explosive such as TNT is oxygen-deficient and it forms relatively large amounts of carbon and hydrogen, while PETN, an oxygen-rich explosive, produces less hydrogen and no carbon.

The compositions of other C-H-N-O explosives were reported by Kamlet and Jacobs (1968). This publication and a paper by Kamlet and Ablard (1968) present discussions of the detonation properties and chemical products of explosives. It should be noted that some authors believe that nitric oxide is an explosion product, though a minor one.

Table 2.1B presents the same data as in Table 2.1A in terms of percentage by weight. This form might be more useful for quickly estimating the total amount of a particular substance deposited in the environment by a test with an explosive charge of a known weight.

It seems reasonable to assume that the products of an underwater explosion will be the same as those of a confined charge and that an unconfined charge is representative of a surface burst.* It is not clear where the transition will actually take place; however, it seems likely that explosives at a depth of two or more charge radii will behave like confined charges.

To properly evaluate the ultimate disposition of explosion products in the marine environment it is necessary to treat them in at least three categories: gases, insoluble solids (particulates), and soluble solids. The gases, of course, are soluble in water; but most of the gaseous products will escape to the atmosphere unless an explosion is exceptionally deep. Initially, the products are contained in a large spherical bubble that pulsates and migrates toward the surface (see Section 2.3.3.2); and the gaseous composition of the bubble is of particular interest for evaluating the rate of solution.

The gases formed by the three explosives considered thus far are listed in terms of percentage by volume in Table 2.2. These values may be readily converted to partial pressure, as in Table 2.3 of Section 2.3.2.1. Water vapor and hydrogen cyanide are treated as gases here, although they partially or completely condense to the liquid state at some later time.

It may be noted that the majority of the products of these explosives are found in the natural environment and are harmless to man and to marine life. This is not necessarily true for carbon monoxide (CO) and hydrogen cyanide (HCN). However, both are rapidly diluted to low levels of concentration, as will be shown in Sections 2.3.3.1 and 2.3.3.2.

* In this report, an explosion is considered to be a surface burst if at least half the charge is exposed to the air.

TABLE 2.1A

DETTONATION PRODUCTS OF CONFINED AND UNCONFINED EXPLOSIONS
(values in moles/mole)

Product		Explosive					
		PETN		HMX		TNT	
Name	Symbol	Confined	Unconfined	Confined	Unconfined	Confined	Unconfined
Carbon Dioxide	CO ₂	3.32	3.50	1.92	1.44	1.25	0.063
Carbon Monoxide	CO	1.61	1.56	1.06	2.65	1.98	5.89
Carbon	C	—	—	0.97	—	3.65	1.01
Nitrogen	N ₂	1.95	2.00	3.68	4.01	1.32	1.36
Water	H ₂ O	3.68	3.45	3.18	2.50	1.60	0.17
Hydrogen	H ₂	0.34	0.51	0.30	1.53	0.46	2.31
Ammonia	NH ₃	0.056	<0.0002	0.395	—	0.162	0.022
Methane	CH ₄	0.004	<0.0002	0.039	—	0.099	0.0092
Hydrogen Cyanide	HCN	—	—	0.008	0.0006	0.020	0.024
Ethane	C ₂ H ₆	—	—	0.001	—	0.004	—

Sources: Ornellas, Carpenter, and Gunn, 1966
Ornellas, 1968

TABLE 2.1B

DETONATION PRODUCTS OF CONFINED AND UNCONFINED EXPLOSIONS
(values in percentage by weight)

Product	Name	Symbol	Explosive					
			PETN		HMX		TNT	
Confined	Unconfined	Confined	Unconfined	Confined	Unconfined	Confined	Unconfined	Confined
Carbon Dioxide	CO ₂		46.22	48.72	28.53	21.40	24.22	1.22
Carbon Monoxide	CO		14.26	13.82	10.02	25.06	24.42	72.64
Carbon	C		—	—	3.93	—	19.30	5.34
Nitrogen	N ₂		17.28	17.72	34.81	37.93	16.28	16.78
Water	H ₂ O		20.97	19.66	19.34	15.21	12.69	1.35
Hydrogen	H ₂		0.22	0.32	0.20	1.04	0.41	2.05
Ammonia	NH ₃		0.30	—	3.42	—	1.21	0.16
Methane	CH ₄		0.02	—	0.21	—	0.70	0.06
Hydrogen Cyanide	HCN		—	—	0.07	0.01	0.24	0.28
Ethane	C ₂ H ₆		—	—	0.01	—	0.05	—

TABLE 2.2
GASEOUS PRODUCTS OF CONFINED EXPLOSIONS
(values in percentage by volume)

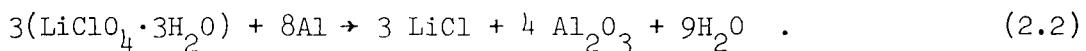
Product		Explosive		
Name	Symbol	PETN	HMX	TNT
Carbon Dioxide	CO ₂	30.283	17.819	18.124
Carbon Monoxide	CO	14.674	9.834	28.715
Nitrogen	N ₂	17.788	34.154	19.139
Water	H ₂ O	33.555	29.508	22.275
Hydrogen	H ₂	3.146	2.727	6.697
Ammonia	NH ₃	0.508	5.520	2.339
Methane	CH ₄	0.036	0.359	1.438
Hydrogen Cyanide	HCN	—	0.071	0.292
Ethane	C ₂ H ₆	—	0.009	0.054

Many explosive compositions currently in use consist of mixtures of different organic explosives or mixtures of these with aluminum. One product of the latter explosives is aluminum oxide (Al_2O_3), which is formed as a white insoluble powder.

A typical percentage of Al_2O_3 by weight for an aluminized explosive would be about 35 percent.

Carbon is always highly visible after a TNT explosion, either as smoke or in a surface pool of blackened water. In the HYDRA IIA Series, conducted by the Naval Radiological Defense Laboratory in 1961 with 10,000-lb charges of HBX-1*, samples of airborne materials included carbon clusters from the explosion and spheroidal aluminum oxide particles, some as large as 250 microns in diameter. Varying amounts of carbon were found in these particles.

Some information is available on a special explosive composition called Lithanol, which was developed to produce an explosion bubble with no permanent gases. The chemical equation for a Lithanol explosion is the following (Murphy, 1963):



Lithium chloride is soluble in water; and in a series of tests conducted with large Lithanol charges in the Caribbean Sea during 1967, water samples were taken at the surface after four of the 1400-lb shots for analysis. It was found that the concentration of lithium averaged about 0.192 mg/l during the first 18 minutes and was reduced to background levels (0.187 mg/l) in possibly 30 minutes. The amount of aluminum oxide was not measured, but it was visible in the surface pools.

It should be mentioned that certain compositions used in detonators contain poisonous substances. These include fulminate of mercury ($\text{Hg}(\text{ONC})_2$), and lead azide ($\text{Pb}(\text{N}_3)_2$). Lead and mercury oxides are formed by the explosion of these compounds. However, the total weight of a detonator charge is generally less than one gram. Detonators containing PETN are more frequently used in Navy test programs.

2.3.2 Background Levels

2.3.2.1 Atmosphere. The major atmospheric gases are nitrogen, oxygen, and argon, and the relative proportions of these three are virtually constant over the entire world. Other gases are found in minute quantities, which tend to vary as a result of industrial pollution, volcanic activity, or biological effects. The most important variable constituents are water vapor and carbon dioxide. The most common gases, and the atmospheric gases possibly formed by conventional explosions are listed in Table 2.3.

Considerable effort has been devoted toward the measurement of the amount of carbon dioxide in the atmosphere during recent years because changes in the concentration of this gas could possibly have long-range effects on the climate (Rasool and Schneider, 1971). The total quantity of the gas in the atmosphere appears to be increasing at the present time; but in addition, numerous variations

* HBX-1 consists of RDX, TNT, Aluminum, and Wax in the following proportions:
40/38/17/5.

TABLE 2.3
ATMOSPHERIC GASES

Name	Symbol	Volume Percentage	Partial Pressure (atmospheres)
Nitrogen	N ₂	78.1	0.781
Oxygen	O ₂	20.9	0.209
Argon	A	0.93	0.0093
Water Vapor	H ₂ O	0 - 3	0 - 0.03
Carbon Dioxide	CO ₂	0.0316	3.16 x 10 ⁻⁴
Methane	CH ₄	1.4 x 10 ⁻⁴	1.4 x 10 ⁻⁶
Nitrous Oxide	N ₂ O	5 x 10 ⁻⁵	5 x 10 ⁻⁷
Hydrogen	H	5 x 10 ⁻⁵	5 x 10 ⁻⁷
Carbon Monoxide	CO	10 ⁻⁵	10 ⁻⁷
Nitric Oxide	NO	None	
Nitrogen Dioxide	NO ₂	4.08 x 10 ⁻⁹	4.08 x 10 ⁻¹¹
Ammonia	NH ₃	2.02 x 10 ⁻⁹	2.02 x 10 ⁻¹¹

Sources: Handbook of Geophysics, 1960
Robinson and Robbins, 1969
Georgii, 1963

have been discovered that can be attributed to natural and manmade causes. These include photosynthesis by plants, venting from soils and rocks, volcanic eruptions, changes in atmospheric pressure, changes in the temperature of sea water, biological activity in sea water, and the burning of fossil fuels. However, for the purposes of this report, an average sea level value of 316 ppm by volume in oceanic regions is sufficiently accurate (Takahashi, 1961; Keeling and Waterman, 1968). The measured values rarely differ from this amount by more than 5 percent.

Relatively little information is available on the concentration of carbon monoxide in the unpolluted atmosphere because of difficulties in measurement. However, relatively clean air sampled in the Arctic and Antarctic regions averages about 0.1 ppm (Robinson and Robbins, 1969).

Ammonia and the oxides of nitrogen are trace gases which play an important role in the formation of aerosol particles in the atmosphere. Of the eight oxides of nitrogen, only N_2O and NO_2 have been detected in the lower atmosphere. These gases and ammonia show considerable variability (Georgii, 1963); the values given in Table 2.3 represent approximate background levels.

The atmosphere also contains solid particles, and the natural atmospheric aerosol has two major parts (Handbook of Geophysics, 1960). Over the oceans, at positions remote from sources of pollution, the marine aerosol consists primarily of particles of sea salt with essentially the same chemical constituents as sea water (see Section 2.3.2.2). The particle radii range from about 0.1 to 30 microns. Continental air contains dust and mineral particles from soils, with the same range of sizes, and it also contains particles less than 0.1 micron in radius, which originate mainly from various kinds of smoke.

As the major constituent of the latter is probably carbon, this part of the atmospheric aerosol might resemble the airborne particulate matter produced by an explosion in the air or at a very shallow position in water. The total aerosol concentration in continental air ranges from 50 micrograms per cubic meter in unpolluted regions to 1000 micrograms per cubic meter over large cities.

The natural atmospheric aerosol is an essential part of the planetary water cycle, as the particulates serve as condensation nuclei for the water vapor in the air. These droplets grow to raindrop size and fall to the surface. In this manner, the sea salts in the marine aerosol may be deposited on land in rainfall to ultimately flow back to the sea.

It is interesting to note that the primary mechanism for the transport of sea salt across the sea-air interface is the bursting of small bubbles. These are formed by the entrainment of air in breaking waves and by the impact of raindrops. The bubble diameters range from about 0.1 to 5 mm (Monahan and Zietlow, 1969). It has been estimated that from 2 to 5% of the ocean is covered by breaking waves at all times and that a bursting rate of possibly 30 bubbles/cm² sec can be found in these regions (Blanchard, 1963).

When a rising bubble reaches the surface, a thin film possibly 2 microns thick, is pushed up. This immediately disintegrates to form from 10 to 100 droplets with diameters of 1 to 20 microns (Moore and Mason, 1954). These droplets evaporate and the sea salt residue remains airborne. Immediately following this, the bottom of the bubble rises into the air in the form of a jet, which breaks up

into possibly five drops with diameters about one-tenth the bubble diameter. As these are relatively large, they usually fall back into the sea without evaporating appreciably. However, their impact may eject tiny droplets to the air. This process has been described in publications such as Blanchard (1963) and Garrett (1967).

It is important to point out that bacteria, surface films, and other contaminants in sea water are also ejected to the air by this natural bubbling process (Garrett, 1967; Blanchard, 1971).

2.3.2.2 Sea Water. Every natural element on earth doubtless exists in sea water, although some are found in extremely low concentrations and a few have not been detected and measured as yet. For example, Horne (1970) presented a table listing the measured concentrations of 74 elements in the sea. The major constituents exist in virtually constant ratios to each other in all parts of the world. The chemicals in the sea are in various forms, e.g., dissolved solids and gases, gases entrapped in bubbles, electrolytes and non-electrolytes, colloids, and solid particles. Some are organic and some inorganic, and many of the former play an important part in life processes. The various cycles and chemical processes that occur are quite complex and will not be discussed here; however, Horne's 1970 publication is a useful reference for the interested reader, as it contains a summary of current knowledge and an extensive bibliography.

Table 2.4 is a list of the chemical elements in sea water (in non-gaseous form) that are also likely to be found in conventional explosives. The table gives representative average values for the oceans, though local variations can be expected for the less common elements. For example, 72 samples of sea water in the Gulf of Mexico had an average content of 2.0 micrograms/liter of particulate aluminum, and the measurements ranged from 0.2 to 10.2 micrograms/liter in value (Feely, 1971). The average concentration was therefore lower than indicated in Table 2.4. It seems likely that semi-enclosed bodies of water, such as the Gulf of Mexico, would be more likely to exhibit such minor deviations in composition than the open oceans.

Table 2.5 lists gases found in solution in sea water. The concentration varies with temperature and salinity. In the case of carbon dioxide, the concentration of dissolved gas in sea water is about 0.3 ml/l. However, CO_2 reacts with water to form carbonic acid (H_2CO_3). This acid then singly and doubly ionizes to form bicarbonate and carbonate ions. The total CO_2 in the carbonate system in sea water is therefore about 45 ml/l, which means that only 0.7% is in physical solution (Kanwisher, 1963a).

The concentrations of hydrocarbons such as methane and ethane in sea water vary because of chemical and biological processes, and in some regions these gases leak from the bottom sediments and go into solution. This is believed to occur in the western part of the Gulf of Mexico, where average concentrations of 38.1×10^{-5} ml/l of methane and 6.03×10^{-6} ml/l of ethane were measured (Frank, et al., 1970).

When a mixture of two or more gases is in contact with water, the solubility of each gas is the same as if it were present at its own partial pressure.

TABLE 2.4
 EXPLOSIVE CONSTITUENTS FOUND IN NATURAL SEA WATER
 (Non-Gaseous)

Name	Symbol	Concentration (mg/l)
Hydrogen	H	108,000
Lithium	Li	0.17
Carbon	C	28*
Nitrogen	N	0.5
Oxygen	O	857,000
Aluminum	Al	0.01
Mercury	Hg	0.00003
Lead	Pb	0.00003

* In compounds

SOURCE: Horne (1970)

TABLE 2.5
GASES DISSOLVED IN SEA WATER

Name	Symbol	Concentration (ml/l)	Temperature (C)	Salinity (0/00)
Nitrogen	N_2	11.4	10	36.13
		9.61	20	36.13
Oxygen	O_2	6.33	10	36.13
		5.16	20	36.13
Carbon Dioxide	CO_2	0.320	10	36.13
		0.214	24	36.13
Carbon Monoxide	CO	23.0×10^{-6}	10	36.13
		19.4×10^{-6}	20	36.13
Methane	CH_4	5.7×10^{-5}		
Ethane	C_2H_6	1.1×10^{-6}		

SOURCES: Sverdrup, et al (1946)
 Lamontagne, et al (1972)
 Green and Carritt (1967)
 Douglas (1965)
 Douglas (1967)
 Riley and Skirrow (1965)

Therefore, air does not dissolve in sea water as a whole, but each gas dissolves in proportion to its solubility and partial pressure. Water in contact with the atmosphere tends to reach equilibrium (i.e., the water is just saturated), and the concentration of the solution of the gas is expressed in the form of Henry's law (Sverdrup, et al, 1946):

$$C_s = \alpha P \quad , \quad (2.3)$$

where:

$$\begin{aligned} C_s &= \text{concentration of the gas in the water,} \\ &\quad \text{ml/l,} \\ \alpha &= \text{solubility coefficient, ml/l-atmos.,} \\ P &= \text{partial pressure of the gas, atmos.} \end{aligned}$$

Table 2.6 presents some solubility coefficients for use with Equation 2.3. It should be noted that the values of α are dependent on temperature, salinity, and pressure; and it is necessary to use tables (e.g., Dorsey, 1940; Douglas, 1965; Green and Carritt, 1967; and Douglas, 1967) when accurate calculations are needed. The values of P for average atmospheric conditions are given in Table 2.3. However, actual values of atmospheric pressure, including the pressure of water vapor, are needed to provide accurate results when in situ studies are conducted.

The assumption that the gases in sea water are in equilibrium with the gases in the atmosphere is probably a good first approximation and is valid when long-period averages are studied. However, oxygen and carbon dioxide are affected by chemical and biological activities, and minor deviations in the concentrations of all gases doubtless occur as a result of normal pressure and temperature changes in the atmosphere and the oceans. Consequently, at a given time or place, the gases in solution may not be in equilibrium, and a flux will take place across the air-sea interface.

The mechanism of transport of gases across this boundary has been described in publications by Kanwisher (1963a; 1963b) and Davies (1963). It is generally assumed that the gas exchange is controlled by the rate of diffusion through a thin, relatively unstirred, surface layer. This layer varies from about 10 to 200 microns in thickness, and the air above and the water below are considered to be well mixed and to have uniform concentrations of gas. The concept of a thin surface layer is also used in studies of heat transfer across the air-sea interface (e.g., Ewing and McAlister, 1960; Saunders, 1967; Wu, 1971).

The model used for gas exchange is sketched in Figure 2.4. It should be stressed that this approach is useful only near the surface, as the structure of the atmosphere and oceans becomes more complex at greater distances. The rate of flux across the surface is given by:

$$\frac{dq}{dt} = A D \frac{\partial C}{\partial z} \quad , \quad (2.4)$$

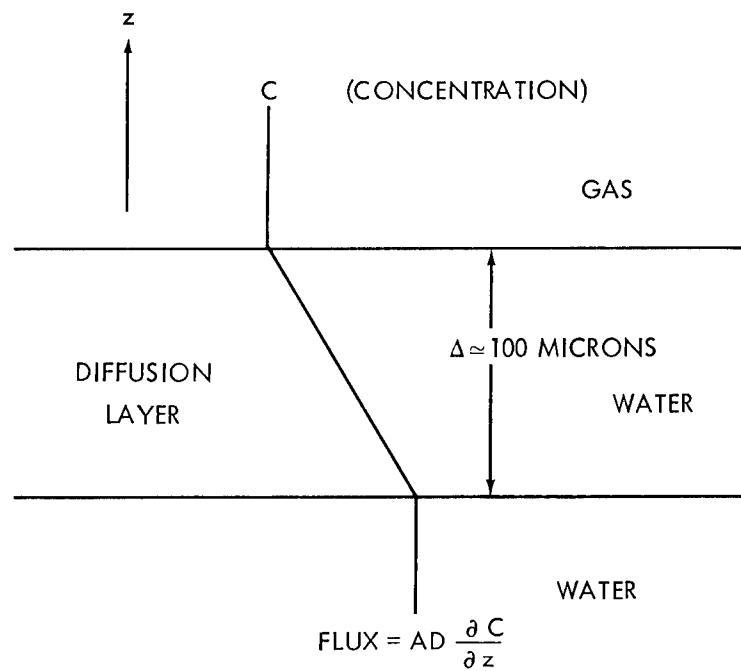
where:

$$\begin{aligned} q &= \text{quantity of gas, ml,} \\ t &= \text{time, sec,} \\ A &= \text{area of surface, cm}^2, \\ D &= \text{diffusivity of gas in water, cm}^2/\text{sec,} \\ C &= \text{concentration of gas, ml/l,} \\ z &= \text{direction perpendicular to the interface,} \\ &\quad \text{cm.} \end{aligned}$$

TABLE 2.6
SOLUBILITY COEFFICIENTS FOR USE IN HENRY'S LAW

Name	Symbol	Solubility Coefficient α (ml/l-atmos)	Temperature (C)	Salinity (0/00)
Nitrogen	N_2	14.6	10	36.13
		12.3	20	36.13
Oxygen	O_2	30.3	10	36.13
		24.7	20	36.13
Carbon Dioxide	CO_2	1012	10	36.13
		677	24	36.13
Carbon Monoxide	CO	23.0	10	36.13
		19.4	20	36.13
Methane	CH_4	40.7		

SOURCES: Douglas (1965)
Douglas (1967)
Green and Carrritt (1967)
Riley and Skirrow (1965)
Lamontagne, et al, (1972)



<u>GAS</u>	<u>D FOR GAS IN WATER *</u> (cm ² /sec)
O ₂	2.0×10^{-5}
N ₂	2.0×10^{-5}
CO ₂	1.6×10^{-5}
H ₂	4.5×10^{-5}
NH ₃	1.1×10^{-5}

* SOURCES: DORSEY (1940)
LE BLOND (1969)

FIG. 2.4 GAS-WATER INTERFACE MODEL

Utilizing a linear gradient of concentration in the diffusion layer (Figure 2.4), and assuming that the concentration of gas in the water is given by Equation 2.3 and that no gas is present above the interface, the relation reduces to the following form:

$$\frac{dq}{dt} = \frac{A D \alpha P}{\Delta} , \quad (2.5)$$

where:

Δ = film thickness, cm,

P = partial pressure of the gas in the water, atmos.

If gas is present above the interface, the relation is:

$$\frac{dq}{dt} = \frac{A D \alpha (P - P_o)}{\Delta} , \quad (2.6)$$

where:

P_o = pressure of the gas, atmos.

The values of the diffusivity of gases in water are all of the order of 10^{-5} cm²/sec. Typical values are included in Figure 2.4. The diffusivity of the gases in air is about 10^4 times as great, which provides the justification for assuming a complete mixing in the lowest level of the atmosphere.

As shown in Table 2.6, the solubility of gases varies considerably, and CO₂ will dissolve faster than the other gases under consideration. The film thickness also varies, and it becomes effectively thinner in the presence of wind and turbulence, which leads to more rapid transport across the interface.

An additional complication occurs in the case of carbon dioxide, as the exchange rate of this gas depends on the pH. When the wind speed is low and the water is quiescent, an enhancement of the transfer rate occurs if the solution pH is greater than 6.0 (Hoover and Berkshire, 1969). However, the importance of this in the open ocean has yet to be evaluated.

The oceans also contain suspended matter, which varies widely in quantity. Along the Atlantic Coast, the amount exceeds 1.0 mg/l within a few kilometers of shore (Manheim, et al, 1970). On a world-wide basis, the average value for inorganic matter is probably less than 0.1 mg/l. Much of this debris consists of soot, fly ash, and processed cellulose, rather than mineral particles. The sources include refuse from ships as well as sewage and the discharge from rivers and estuaries.

2.3.2.3 Inland Waters. As inland waters include lakes, rivers, bays, and estuaries, an almost infinite range of possible levels of chemical content is possible. In many cases, this is a result of man-made pollution; however, in a clean estuarine system, almost pure sea water may be found at the mouth while fresh water enters at the sources. Various degrees of mixing occur at intermediate points and some density stratification usually exists.

In an estuary, the amounts of background constituents at a given location can be estimated by the use of a simple mixing model and a knowledge of the composition of the fresh water and sea water inputs (Warner, 1972). This approach is useful for identifying polluting substances, if a water sample contains a chemical that is not accounted for by the model.

Sverdrup, et al (1946), listed the compositions of dissolved solids in the Mississippi, Columbia, and Colorado Rivers. These showed considerable variation, and each river in the world is probably unique in regard to chemical content. The same is doubtless true of lakes.

Certain lakes, such as the Great Salt Lake in Utah and Mono Lake, California, require special consideration. For example, at Mono Lake, the percentage by weight of dissolved chemicals is about double that of sea water, and the specific gravity is about 1.05. The water is very corrosive. The bottom is covered with deposits of organic material, silt, and sand to a depth of 12 feet.

Chemical pollutants in the bottom mud are not necessarily the same as in the water. For example, heavy metals have been found in Potomac River mud from Washington, D. C. to points 100 miles downstream (Profile, 1971). The concentrations during August 1970 were greatly in excess of any reported for sea water, with peak levels of over 60 ppm for cadmium and copper, near 50 ppm for nickel, about 2800 ppm for zinc, 1700 ppm for manganese, about 80 ppm for lead and chromium, and 25 ppm for cobalt.

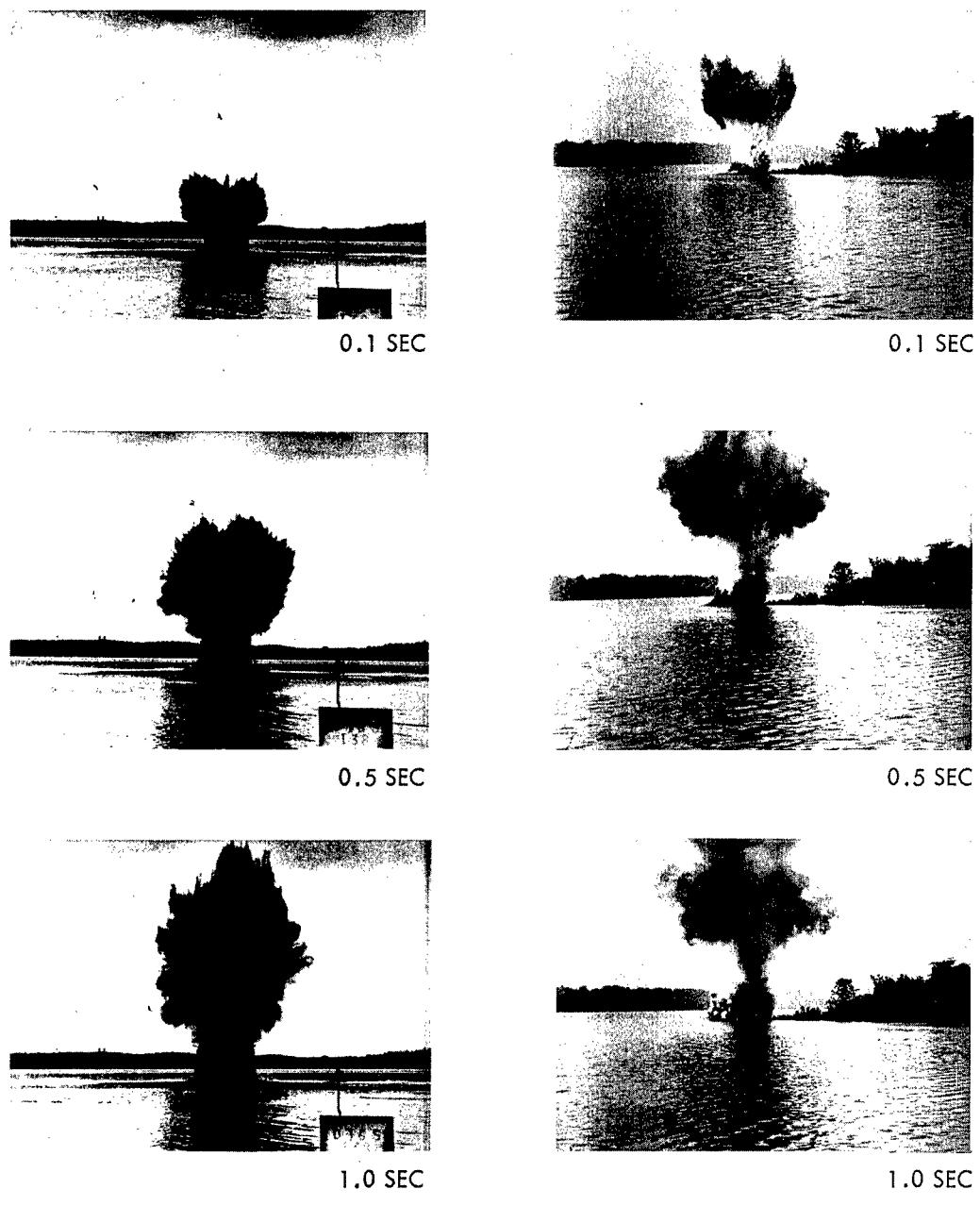
In the Chesapeake Bay, sediment samples near Annapolis showed the following concentrations of metals: lead (60-11 ppm), copper (54-18 ppm), cobalt (355-16 ppm), nickel (58-27 ppm), and vanadium (135-70 ppm). The highest concentrations were observed at the surface of the sediments. The nearby Patuxent River was found to be relatively unpolluted (Pyzik and Sommer, 1972). The chemical composition of the Bay waters was investigated by Newcombe, et al (1939), who found fairly complex variations with season and geographical location. This is to be expected because of the many major tributaries and drainage basins in the estuary system.

If explosion tests are conducted in a location where the background levels of possibly harmful chemicals in the water and sediment are not known, it may be advisable to analyze samples prior to testing. If this is not done, it is possible that future investigators would attribute the presence of metals or other solids to the explosions.

2.3.3 Transfer and Dilution Mechanisms

2.3.3.1 Atmosphere. As indicated in Section 2.3.1, explosion products may be gaseous or solid, and the latter may be soluble or insoluble in water. In the case of a water surface burst, virtually all of the products become airborne and a black smoke cloud is clearly visible from explosives such as TNT (see Figure 2.5). A surface burst also produces a cavity in the water, and spray from the edge of the cavity is ejected into the air, thereby entraining some of the solid products. Consequently, a relatively small pool of blackened water remains at the surface.

Water surface bursts of conventional explosives have received only limited attention. To provide an estimate of atmospheric pollution, the most conservative



A. $d = 0$ $d/A_1 = 0$

WEIGHT = 100 LB

B. $d = 20$ FT $d/A_1 = 0.11$

FIG. 2.5 SURFACE AND VERY SHALLOW EXPLOSIONS

procedure is the assumption that all the products become airborne. In the case of an air burst, if the gases expand to atmospheric pressure without mixing with air, their volume should be about 27 W cubic feet, according to theoretical studies (Brode, 1959; Groves, 1963). However, this value seems unrealistically small, probably because of the neglect of atmospheric mixing.

Explosions just beneath the surface form a smoke crown with a radius equal to about $11.3 W^{1/3}$ feet (Milligan and Young, 1954). As the crown is roughly spherical, its volume is approximately equal to 6000 W cubic feet. This may be utilized as the initial volume containing the explosion products, air, and water for both surface and very shallow bursts. The gases and a portion of the solids can be expected to remain airborne. Table 2.7 provides an estimate of the concentrations of gases in the crown, if all of the products are contained within the smoke crown at the time of its formation. The values in the table are therefore an upper limit.

The density of a smoke crown is not known, but is assumed to be negligibly different from that of the atmosphere for calculation purposes.

Hydrogen cyanide is of special interest because it is poisonous in low concentrations. The threshold limit value for HCN vapor is a concentration of 10 parts per million (Steere, 1971). This is the condition to which nearly all workers may be repeatedly exposed daily without adverse effect. As the initial concentration in the smoke crown is 5.30 ppm, no harmful effects can be anticipated.

In the case of carbon monoxide, the threshold limit value in air is 50 ppm. This is lower than the smoke crown value; but as indicated above, it represents a concentration to which exposure is permissible for a period of eight hours. Concentrations of 400-500 ppm can be inhaled for one hour without appreciable effect (Braker and Mossman, 1970).

The gases in the smoke crown are rapidly diluted by turbulent mixing; and as a rough guide, it may be assumed that the maximum concentration decreases with distance to the 1.50 power (Slade, 1968). A person 100 meters from an explosion would therefore be exposed to a possible CO concentration of only about 0.5 ppm, if he is directly downwind.

Ammonia is an irritant, but the concentration in the smoke crown is below the level that will cause irritation of the eyes, nose, throat, and lungs (Braker and Mossman, 1970). Oxides of nitrogen are possibly formed in trace amounts by explosions, but these would also be at a concentration well below those needed for the initiation of symptoms.

Even if the effects considered here are additive, the combined effect is of no concern to individuals directly downwind of an underwater explosion.

Significant changes take place in surface effects when the explosion depth is increased, although the gaseous products are ejected to the air even by relatively deep explosions. In this case, the products form a spherical bubble that undergoes a series of oscillations while it migrates toward the surface (Cole, 1948). Products are transferred from the bubble to the ambient water by various means, but the arrival of the bubble at the surface results in the ejection of most of the gases. The surface manifestations decrease in size and energy with increasing depth of burst for a given charge weight.

TABLE 2.7
TNT PRODUCTS IN A SMOKE CROWN

Product		Concentration (ppm by volume)		
Name	Symbol	Crown	Atmosphere	T.L.V.*
Carbon Dioxide	CO ₂	329	316	5000
Carbon Monoxide	CO	522	0.1	50
Nitrogen	N ₂	348	781,000	—
Water	H ₂ O	405	20,000	—
Hydrogen	H ₂	122	0.5	—
Ammonia	NH ₃	42.5	0.00002	50
Methane	CH ₄	26.2	1.4	—
Hydrogen Cyanide	HCN	5.30	—	10
Ethane	C ₂ H ₆	0.98	—	—

* Threshold Limit Value

It is convenient and practical to employ the calculated maximum radius of the bubble (A_1) during its first expansion as a characteristic length for scaling and prediction purposes. This method is not rigorous, and A_1 is fictitious at shallow depths; however, this approach is sufficiently accurate for current purposes. More extensive discussions of explosion scaling are available in publications by Cole (1948), Snay (1961), and Young, (1965).

The maximum bubble radius for a TNT explosion is given by the following equation (Cole, 1948):

$$A_1 = 12.6 \frac{W^{1/3}}{Z^{1/3}}, \quad (2.7)$$

where:

A_1 = maximum radius of the explosion bubble during its first oscillation, ft

Z = hydrostatic pressure at the depth of explosion, ft of water (usually taken as $d + 33$ ft, with d = depth of explosion in ft).

Geometric scaling of the explosion bubble is given simply by the ratio of the explosion depth, d , to A_1 . Figure 2.6 has been taken from a report by Young (1971) to show the expected surface phenomena of explosions at different values of d/A_1 . The following description has been condensed from material presented in that report.

In the very shallow category ($d/A_1 < 0.20$), a roughly spherical black smoke crown is formed above an almost perfectly cylindrical white column (Figure 2.5). A central jet then emerges above the crown and rises to a height of about ten times the column diameter, carrying a portion of the smoke with it. The water and solids drop back to the surface to form a roughly circular pool, but some finer particles and droplets are carried downwind, leaving a light deposit on the surface.

At slightly greater depths ($0.20 < d/A_1 < 1.0$), the smoke crown disappears and a tall cylindrical column of water and spray can be seen, to be followed rapidly by radial plumes that emerge at the base (Figure 2.7A). It would be expected that all of the gaseous explosion products would enter the atmosphere at these depths but that only a small percentage of solids would become airborne, possibly as a result of the evaporation of small droplets.

Between reduced depths (d/A_1) of 1.0 and 4.0, the plume phenomena become more complex because the explosion bubble can complete one or more oscillations as it migrates upward (see Section 2.3.3.2). In some cases, the plumes are predominantly radial (Figure 2.7B), while in others they resemble the vertical plumes in Figure 2.7A. Within this range, possibly 90% of the product gases escape to the atmosphere while virtually all of the solids remain in the water. The mechanisms of transfer include the emergence of the explosion bubble, small-scale bubbling at the surface, and possibly diffusion across the surface.

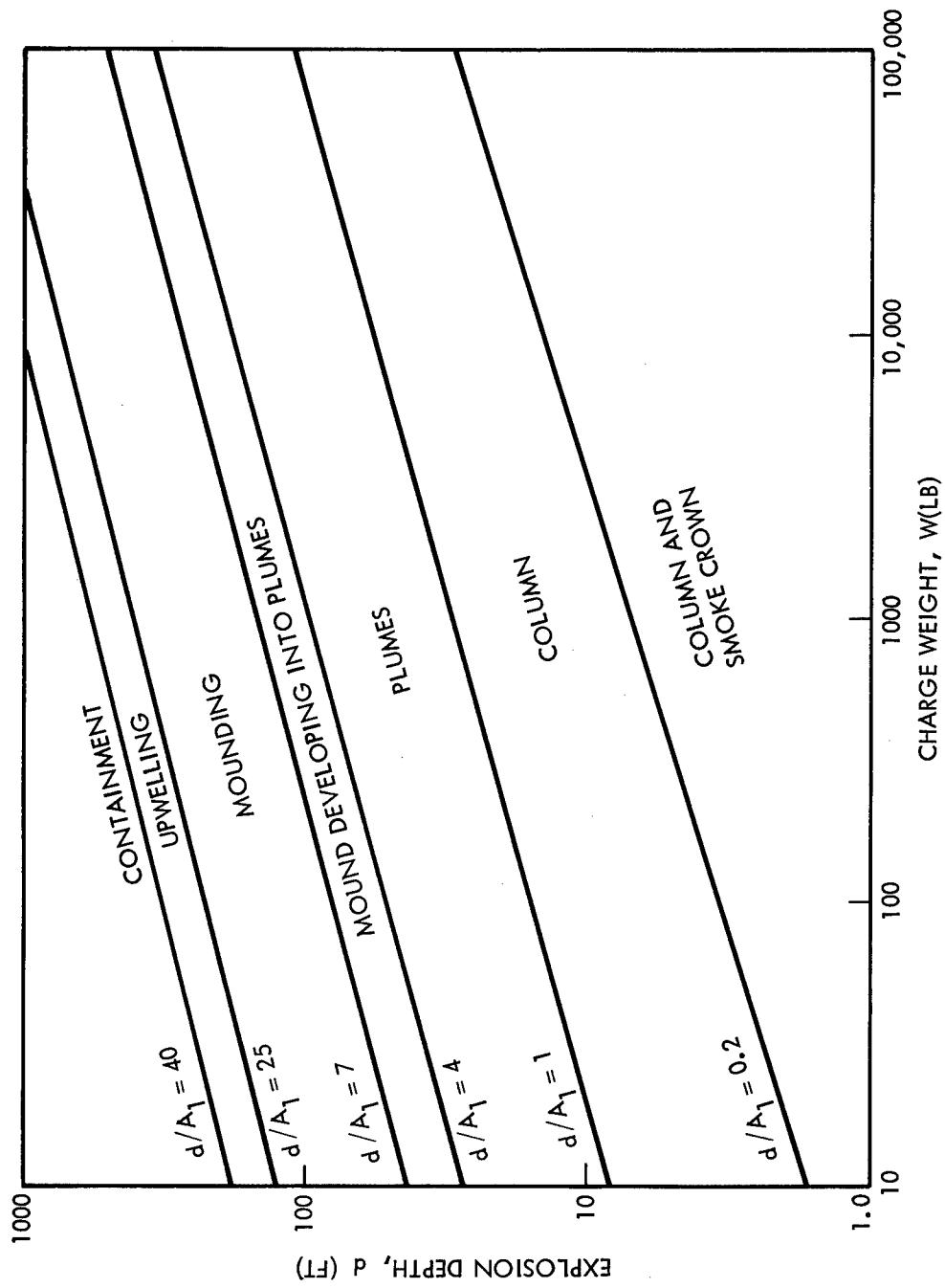


FIG. 2.6 SURFACE EFFECTS OF CONVENTIONAL FREE-WATER EXPLOSIONS

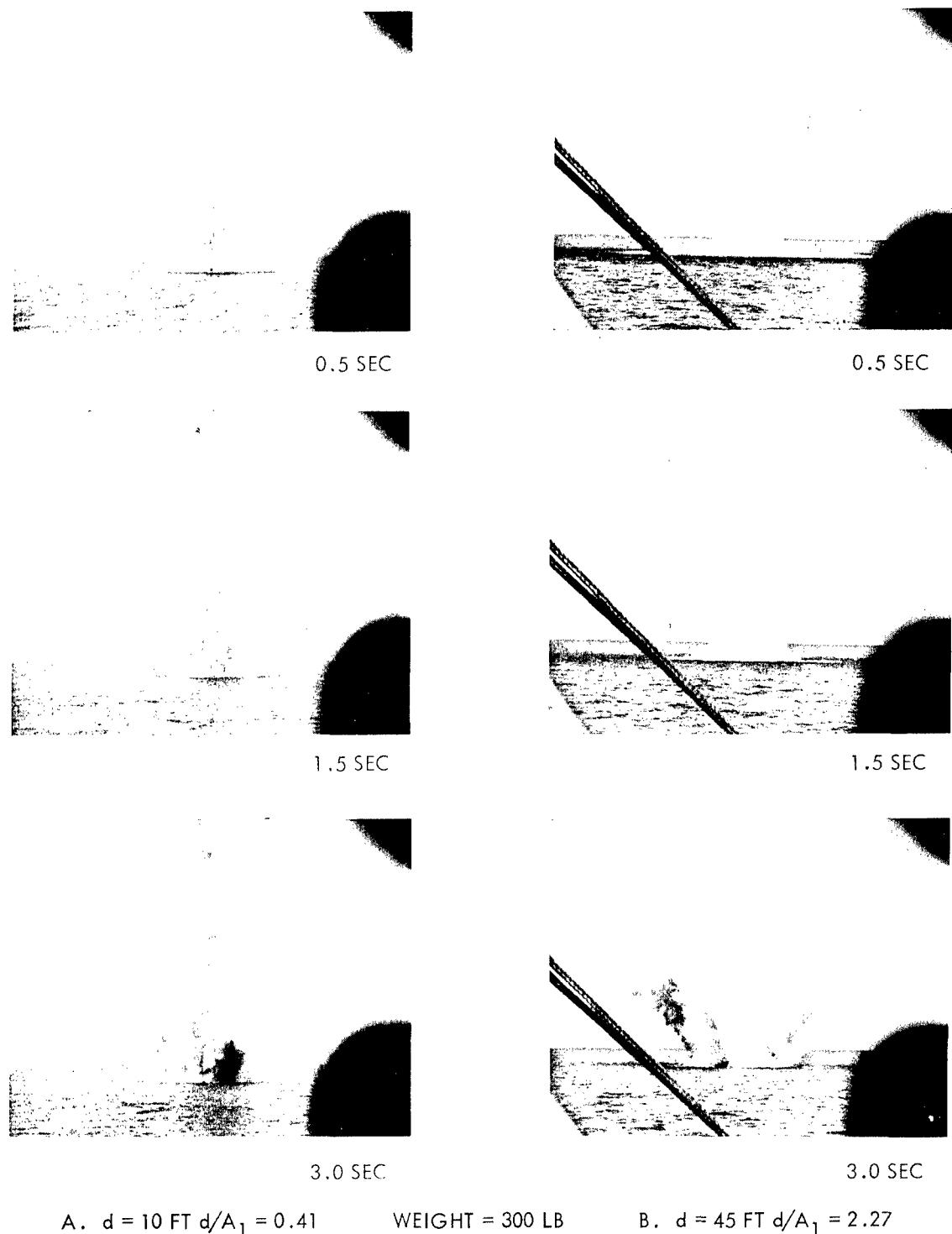


FIG. 2.7 PLUME PHENOMENA OF SHALLOW AND DEEP EXPLOSIONS

Figure 2.8 illustrates the phenomena to be expected between reduced depths (d/A_1) of 4.0 and 7.0. When the bubble emerges, a rough mound of water rises above the surface and then erupts into a large number of plumes. More than half of the gaseous explosion products should be expelled to the atmosphere.

At greater depths ($7.0 < d/A_1 < 25$), only a smooth hemispherical mound appears (Figure 2.9). This subsides rapidly and spreads out laterally to form a surface pool. However, in this region, it is also expected that more than half of the gaseous products will be expelled.

When explosions occur at reduced depths (d/A_1) between 25 and 40, no elevation or depression of the surface occurs, but a rising current of water and explosion products spreads out radially at the surface. This process is called upwelling. At reduced depths in excess of 40, no visible surface phenomena are expected and the products should be contained, though the possibility remains that tiny undissolved gas bubbles could float to the surface after a considerable period of time. This should be a negligible effect for environmental considerations.

Figure 2.10 is presented to provide some guidance concerning the vertical extent of the plume phenomena. It seems likely that all explosion products injected into the air would remain beneath the heights shown in the figure until carried downwind and acted upon by atmospheric diffusion mechanisms.

Figure 2.11 was prepared on the basis of very limited information to provide estimates of the disposition of gaseous material after an underwater explosion. This information can be used to roughly estimate the atmospheric concentration.

2.3.3.2 Sea Water. The explosion phenomena that occur beneath the water surface cannot be observed directly in field tests with relatively large charges. However, a limited amount of underwater photography of small explosions (6 lb) at sea has been accomplished, and hundreds of experiments with gram-size charges have been photographed in tanks. By combining the model studies with related observations of surface effects, a good understanding of the sub-surface bubble behavior has been achieved.

As indicated previously, the products of a deep explosion in water expand to form a spherical bubble. When fully expanded, the internal pressure is lower than the hydrostatic pressure at the depth of burst. The bubble then collapses to a minimum size, whereupon it re-expands almost as though a weak second explosion has occurred. This first collapse of the bubble results in an appreciable loss of energy, a certain amount of turbulent mixing with the surrounding water, and probably the generation of small bubbles.

During the subsequent migration of the main bubble, the pulsations gradually become weaker, and the bubble develops an internal circulation. It resembles a spherical vortex at this stage. Eventually, the circulation stops, and the bubble acquires a hemispherical shape. It gradually erodes at the rear while the leading edge remains smooth. Explosion products are probably deposited in the turbulent wake of the bubble until it disintegrates into a cloud of tiny bubbles. In some cases, relatively large bubbles move out of the cloud and reach the surface first. In the deepest shots on record, the vortex becomes unstable and breaks up into a cloud of bubbles after migrating a relatively short distance. Some of these effects are shown in the photographs in Figures 2.12 and 2.13. The higher tank acceleration in Figure 2.13 resulted in a greater scaled depth of explosion.

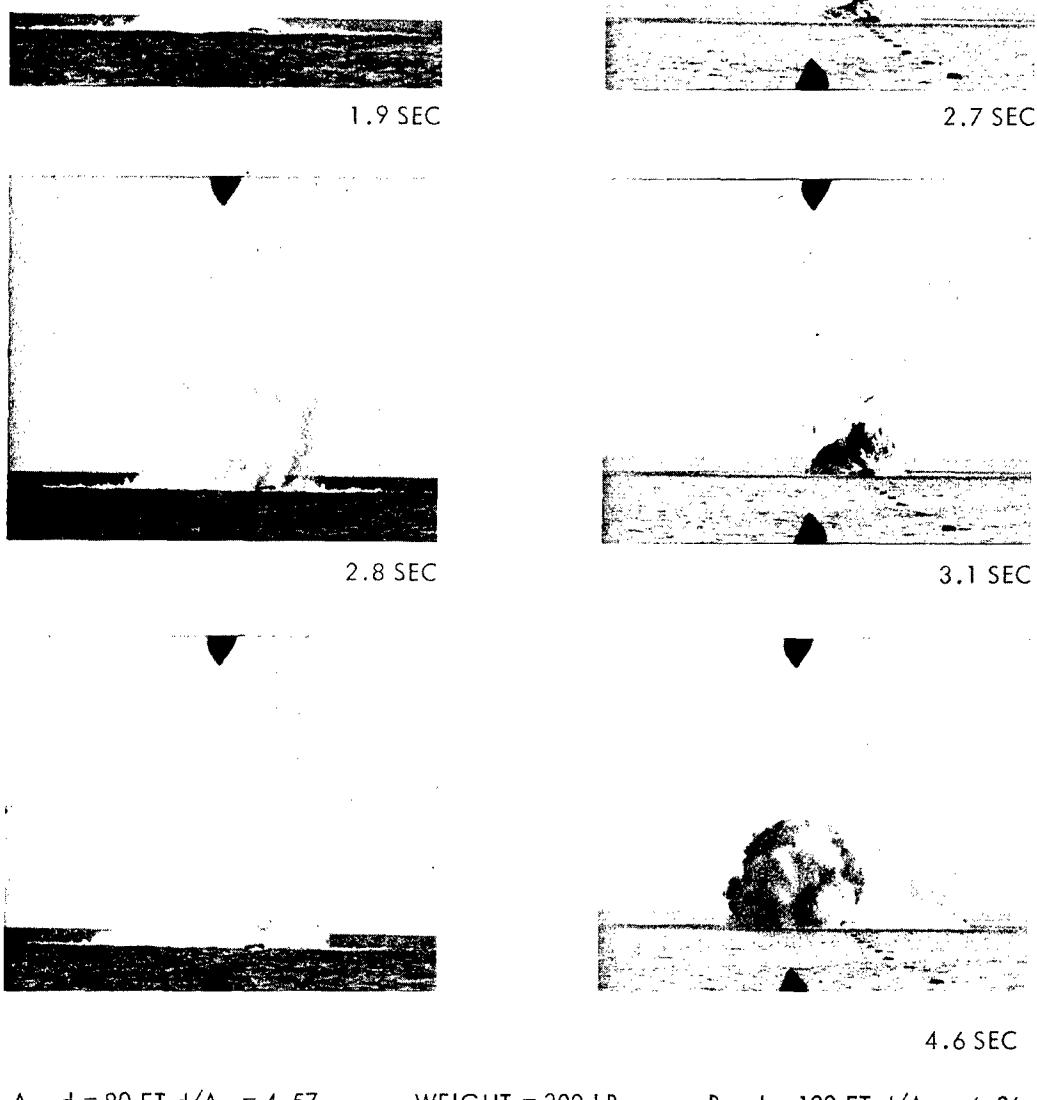
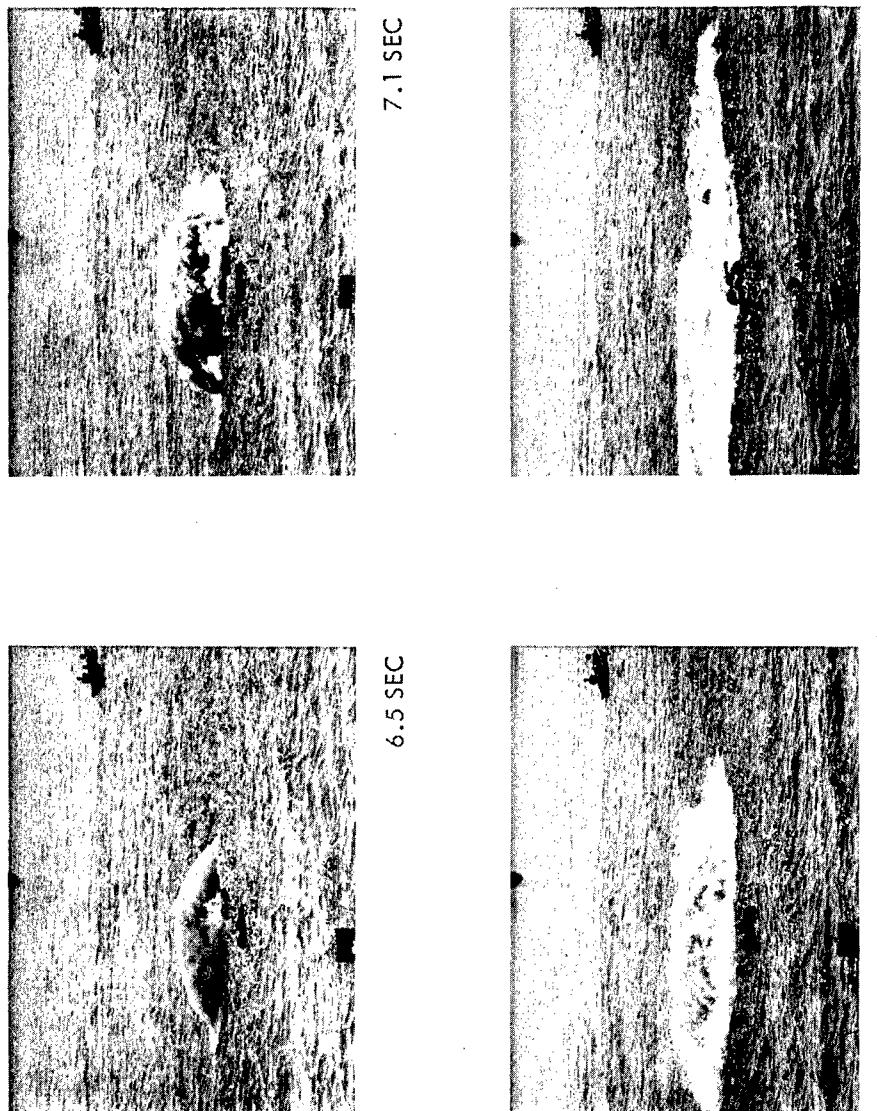


FIG. 2.8 MOUND AND PLUME FORMATION BY VERY DEEP EXPLOSIONS



$d = 100 \text{ FT}$ $d/A_1 = 8.85$ WEIGHT = 50 LB

FIG. 2.9 MOUND DEVELOPMENT AFTER A VERY DEEP EXPLOSION

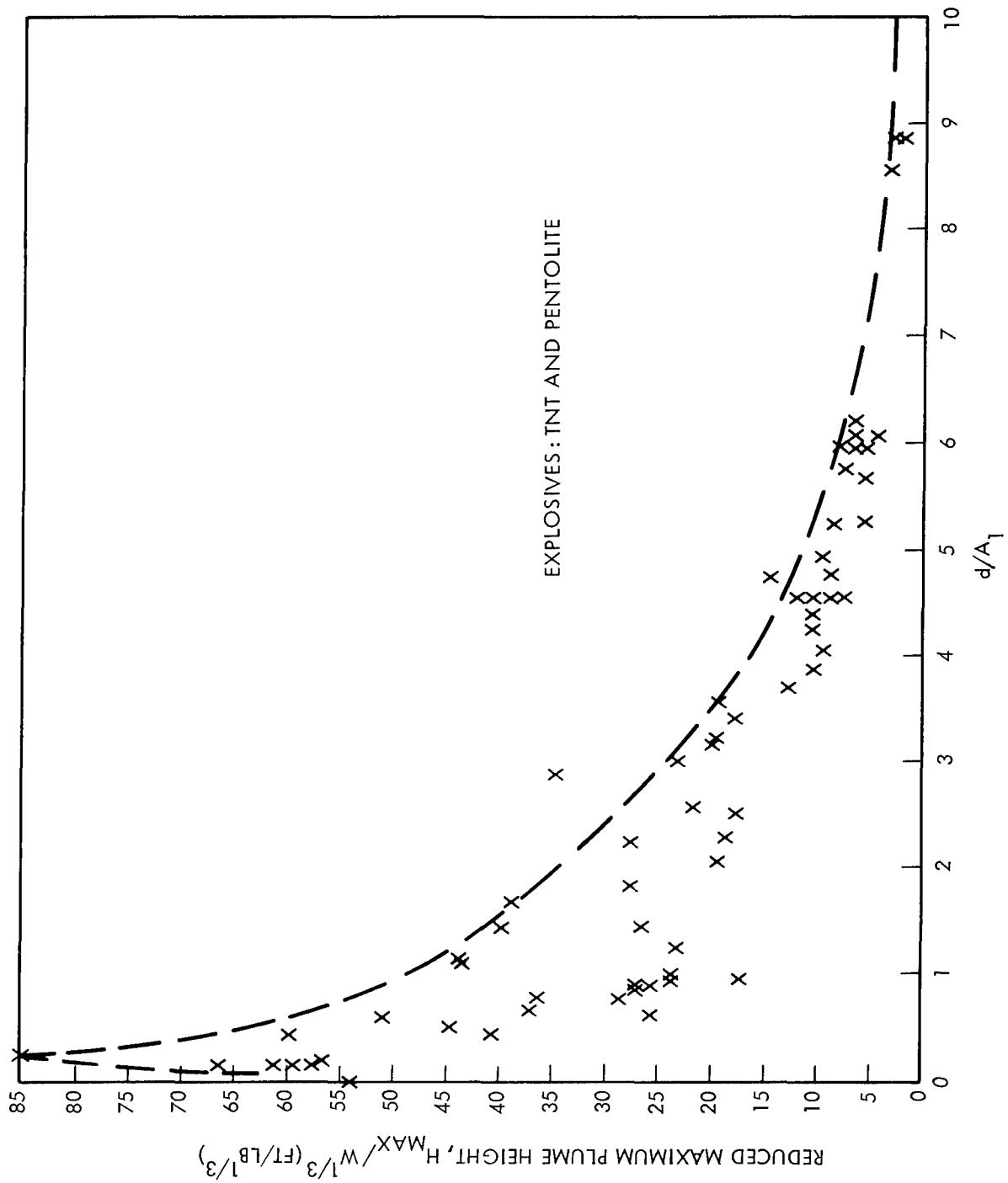


FIG. 2.10 PLUME HEIGHTS

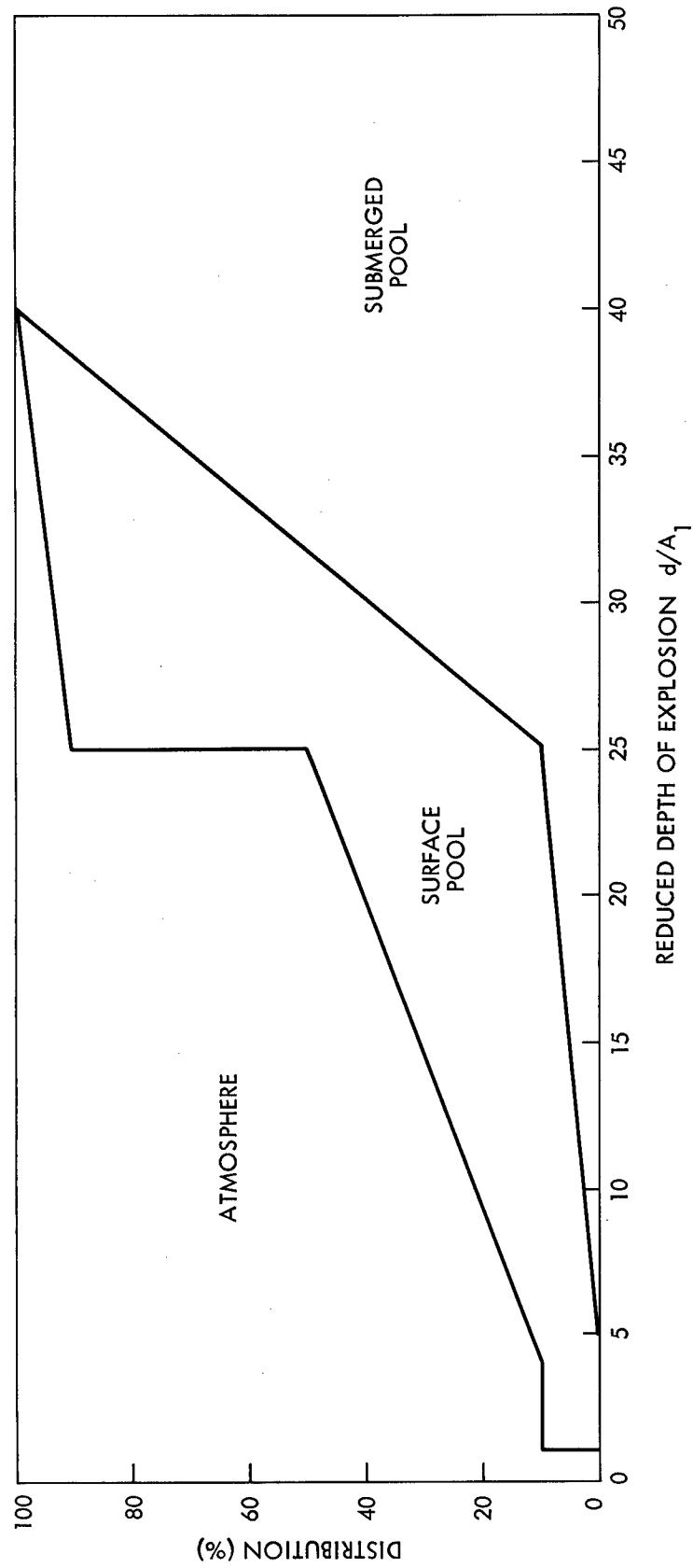


FIG. 2.11 ESTIMATED DISTRIBUTION OF PRODUCT GASES FROM UNDERWATER EXPLOSIONS

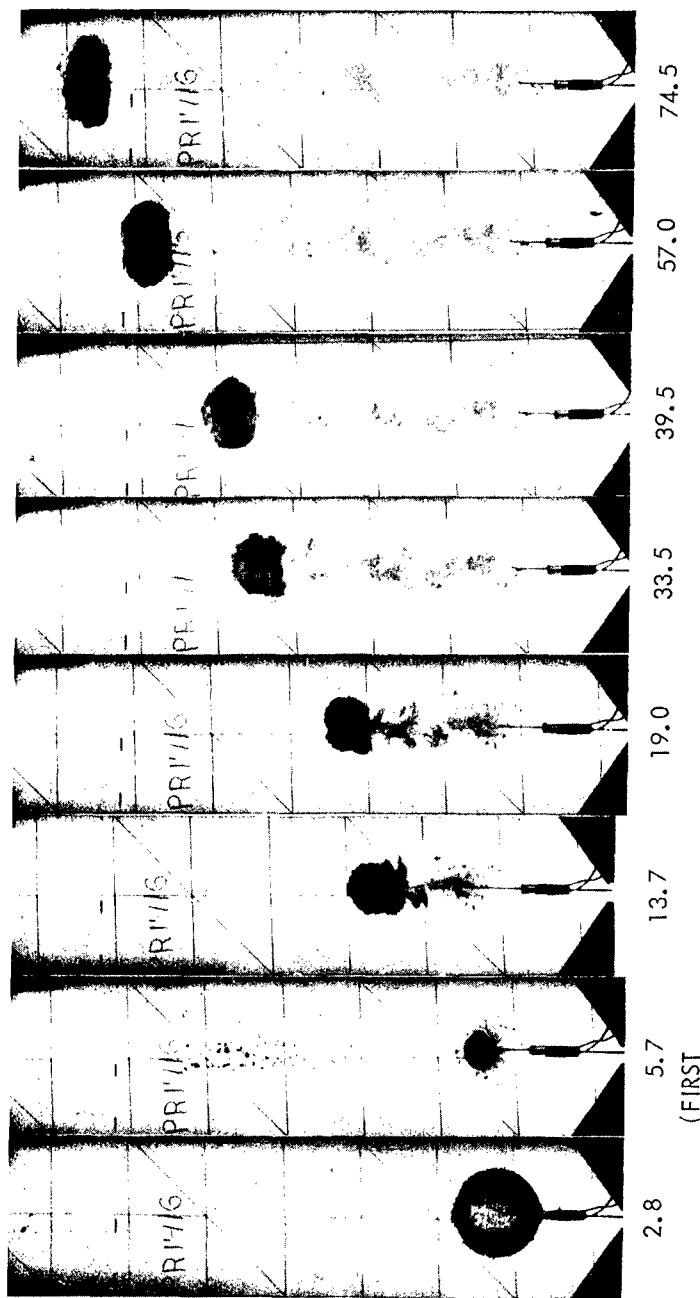


FIG. 2.12 BUBBLE MIGRATION IN ACCELERATED TANK EXPERIMENT - SHOT 1416
(ACCELERATION = $48 \text{ g}^1 \text{s}^{-2}$)

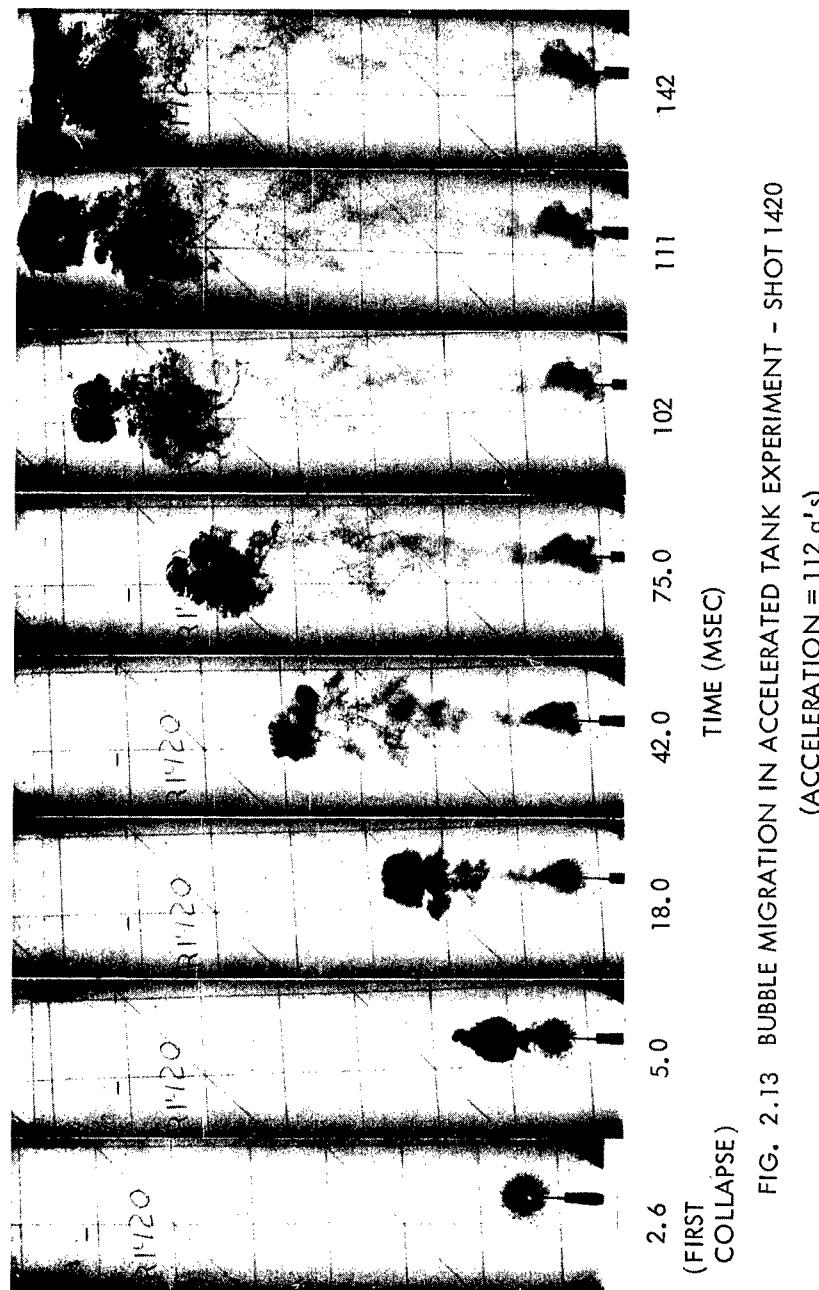


FIG. 2.13 BUBBLE MIGRATION IN ACCELERATED TANK EXPERIMENT - SHOT 1420
(ACCELERATION = 112 g's)

If a bubble reaches the surface while it is pulsating, spectacular plume development may be observed (e.g., Figures 2.7B and 2.8). If a passive hemispherical bubble emerges, a mound is formed (Figure 2.9), while, if the bubble disintegrates into a swarm of tiny bubbles, only an upwelling is observed at the surface. If the explosion is at an excessive depth ($d/A_1 > 40$), these bubbles are not seen. In all cases except the latter, a surface pool is formed. The mechanisms differ, as the pool is formed by the emergence of the bubble and the spillover of the plumes in relatively shallow shots, and by an upwelling current in deeper cases. It also seems likely that material reaches the surface in the wake of the rising large bubbles.

While a bubble is rising, gases will diffuse across the boundary, just as in the case of the air-sea interface. A surface layer should exist on each bubble interface; however, this layer will be effectively thin because the bubbles are moving upward and the surface may be rough because of turbulence. Other factors involved are the effects of surface tension on very small bubbles and the fact that a bubble will expand when it moves into a region of lower hydrostatic pressure (Le Blond, 1969). It is also known that a bubble swarm, or cloud, will rise faster than individual bubbles and that the rate of diffusion may be affected by the presence of other bubbles (Gal-Or and Hoelscher, 1966). In addition, impurities on a bubble surface will affect the rate of solution.

To provide a preliminary estimate, most of these factors may be ignored and a simple model utilized, as sketched in Figure 2.14. The gases dissolved in the medium may be assumed to be in equilibrium with the atmosphere (Table 2.5); the gases in the bubble are those listed in Table 2.2. Because of differing rates of solution, the bubble composition will change while the bubble migrates toward the surface.

The behavior of bubbles of different gas mixtures has been investigated by Wyman, et al (1952). In the case of air bubbles dissolving at high hydrostatic pressure, for example, it was shown that the bubbles gradually became richer in nitrogen because the solubility of oxygen is about double the solubility of nitrogen.

Consider, for simplicity, a passive bubble of a single gas dissolving in water. The rate of change in bubble radius is given by the following equation (Wyman, et al, 1952):

$$\frac{dr}{dt} = - \frac{RTD\alpha}{\Delta} \left(\frac{P_B - P}{P_B} \right) , \quad (2.8)$$

where*:

r = bubble radius, cm,

R = universal gas constant, $\text{cm}^3\text{-atmos.}/\text{mole deg.}$

T = absolute temperature, K,

D = diffusivity of gas in water, $\text{cm}^2/\text{sec.}$

α = solubility coefficient, moles/ $\text{cm}^3\text{-atmos.}$ *,

P_B = pressure in the bubble, atmos.,

P = partial pressure of gas in the water, atmos.,

Δ = thickness of the diffusion layer, cm.

* The units used here for α differ from those in Table 2.6 and Equations 2.3, 2.5, and 2.6.

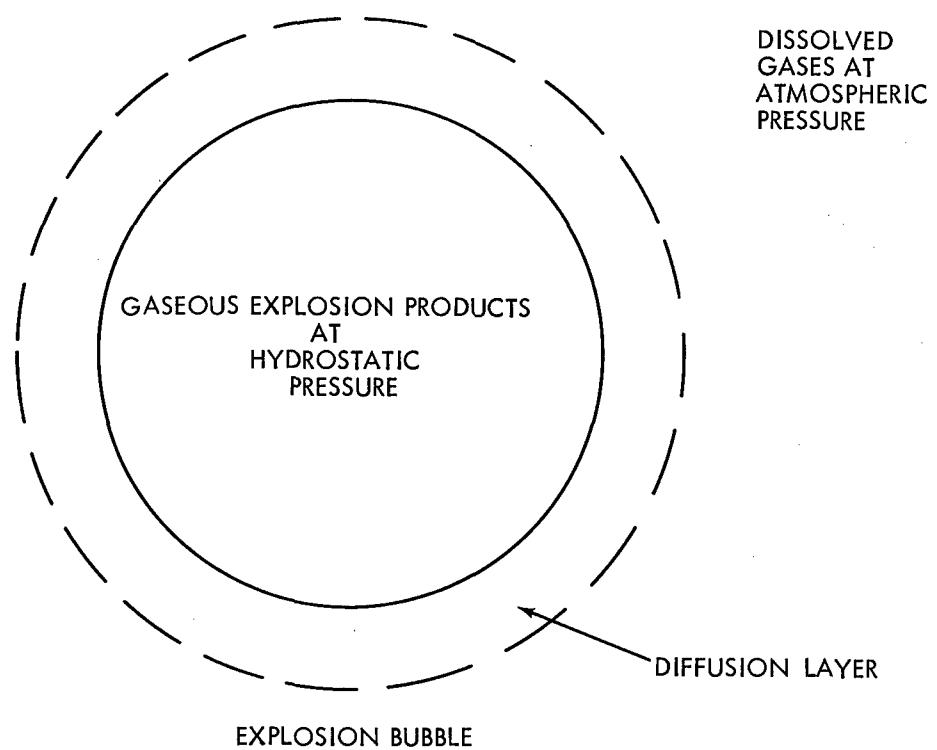


FIG. 2.14 BUBBLE DIFFUSION MODEL

At a depth of 200 meters, $P_B = 21$ atmospheres. If the gas under consideration is oxygen, $P = 0.209$ atmosphere, $\alpha = 4.41 \times 10^{-6}$ moles/cm³-atmos, $D = 2.0 \times 10^{-5}$ cm²/sec, $R = 82.05$ cm³-atmos/mole deg, T may be taken as 293 K and d estimated to be 0.02 cm. In this case $dr/dt = -1.05 \times 10^{-4}$ cm/sec.

If a bubble contains pure carbon dioxide, and $P = 3.16 \times 10^{-4}$ atmosphere, $\alpha = 60.8 \times 10^{-6}$ moles/cm³-atmos, $D = 1.6 \times 10^{-5}$ cm²/sec, and $T = 297$ K, then dr/dt is equal to -1.18×10^{-3} cm/sec, which is a relatively rapid rate of shrinkage by molecular diffusion.

It is evident from the order of magnitude of these results that an explosion bubble that remains intact will dissolve relatively slowly and will change only slightly before reaching the surface. The times of arrival of bubbles of constant volume that originate at a depth of 200 meters are given in Figure 2.15, which also shows calculated bubble migration velocities. The velocities of pulsating explosion bubbles are averages and are shown in relation to the maximum radius A_1 .

Data for the rate of disappearance of air bubbles in water were published by Wyman, et al (1952); these may be used as a rough guide to the possible behavior of bubbles of explosion gases. The data showed that air bubbles with an initial radius of about 0.2 cm persist about 40 minutes at a depth of 200 meters and about 50 minutes at a depth of 10 meters. These values are consistent with those calculated from Equation 2.7.

It is clear that only very small bubbles can dissolve while migrating to the surface, even from relatively deep explosions. It therefore seems likely that even the explosions at the "containment" depths would eventually leak some gases to the atmosphere, but this would certainly be at a slow rate and would be difficult to detect.

A simplified model of the surface pool was developed by Young (1971) to estimate the physical extent at the time of stabilization, i.e., after the kinetic energy has been dissipated and the pool is at rest. The following equations can be used for this purpose:

$$R_{\max} = 59 W^{1/3}, \quad (2.9)$$

$$h_{\max} = 1.6 W^{1/3}, \quad (2.10)$$

$$V_{\max} = 18,000 W, \quad (2.11)$$

$$t_{\max} = 5 W^{1/3}, \quad (2.12)$$

where:

R_{\max} = radius of the surface pool at stabilization, ft,

h_{\max} = depth of the surface pool at stabilization, ft,

V_{\max} = volume of the surface pool at stabilization, ft³,

t_{\max} = time of pool stabilization, min.

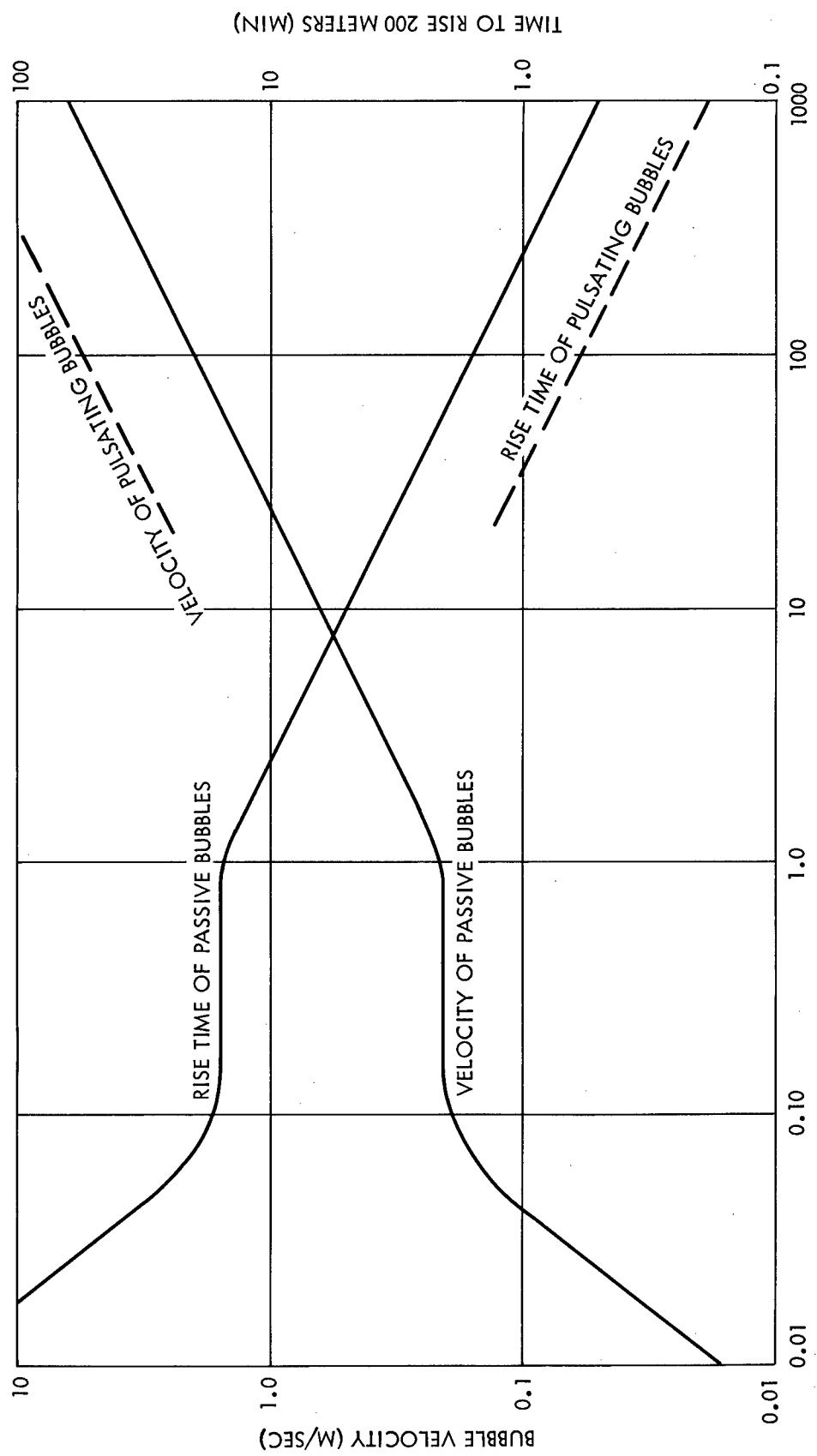


FIG. 2.15 MIGRATION OF BUBBLES

Explosion products remaining in the water should be either in the surface pool or in a submerged vertical cylinder extending from the depth of burst to the surface with a diameter equal to $2A_1$. Figure 2.11 gave the estimated distribution of gaseous products and Figure 2.16 provides an estimate of the distribution of solids.

These values are unverified, and for environmental studies in which it is more important to demonstrate the absence of a hazard than to determine the exact nature of a phenomenon, it is simpler and more effective to take a limiting situation, i.e., a "worst case", and assume that all of the products remain in the surface pool.

As an example, consider the hydrogen cyanide produced by a TNT explosion. The weight of HCN may be taken as kW lb, where k is a coefficient obtained from Table 2.1B by dividing percentages by 100 ($k = .0024$ in this case). Taking the volume of the pool from Equation 2.11, the concentration in the pool becomes

$$C_o = \frac{kW}{18,000W} , \quad (2.13)$$

where:

$$C_o = \text{concentration in surface pool, lb/ft}^3.$$

For comparison with oceanographic data, Equation 2.13 may be expressed as follows:

$$C_p = 0.889 k , \quad (2.14)$$

where:

$$C_p = \text{concentration in surface pool, mg/l.}$$

In this example, the result is a concentration of HCN of 2.13×10^{-3} milligrams/liter. The concentrations of all the products of a TNT explosion are shown in Table 2.8, based on the assumption that all remain in the surface pool. This is particularly unrealistic for the gases, and all values are doubtless higher than would be observed. The table also includes average sea water background values.

After the kinetic energy of the surface and underwater pools has been expended, the pools appear to stop expanding. However, a slow growth continues as a result of small-scale oceanic turbulence, and at the same time the pools may be distorted by large-scale irregularities and transported by currents. This process has been described in detail in publications by Okubo (1962), and Pritchard, et al (1971).

Several theoretical solutions have been obtained for the diffusion of substances introduced instantaneously at a point in the sea. These have been summarized by Okubo (1962) and by Smith (1967). The theories may be utilized if detailed calculations are needed for the spread of the products of a conventional explosion; however, for the purposes of this report, only some approximate estimates of the significant effects are needed. For simplicity, a radially symmetric two-dimensional horizontal diffusion process will be assumed to take

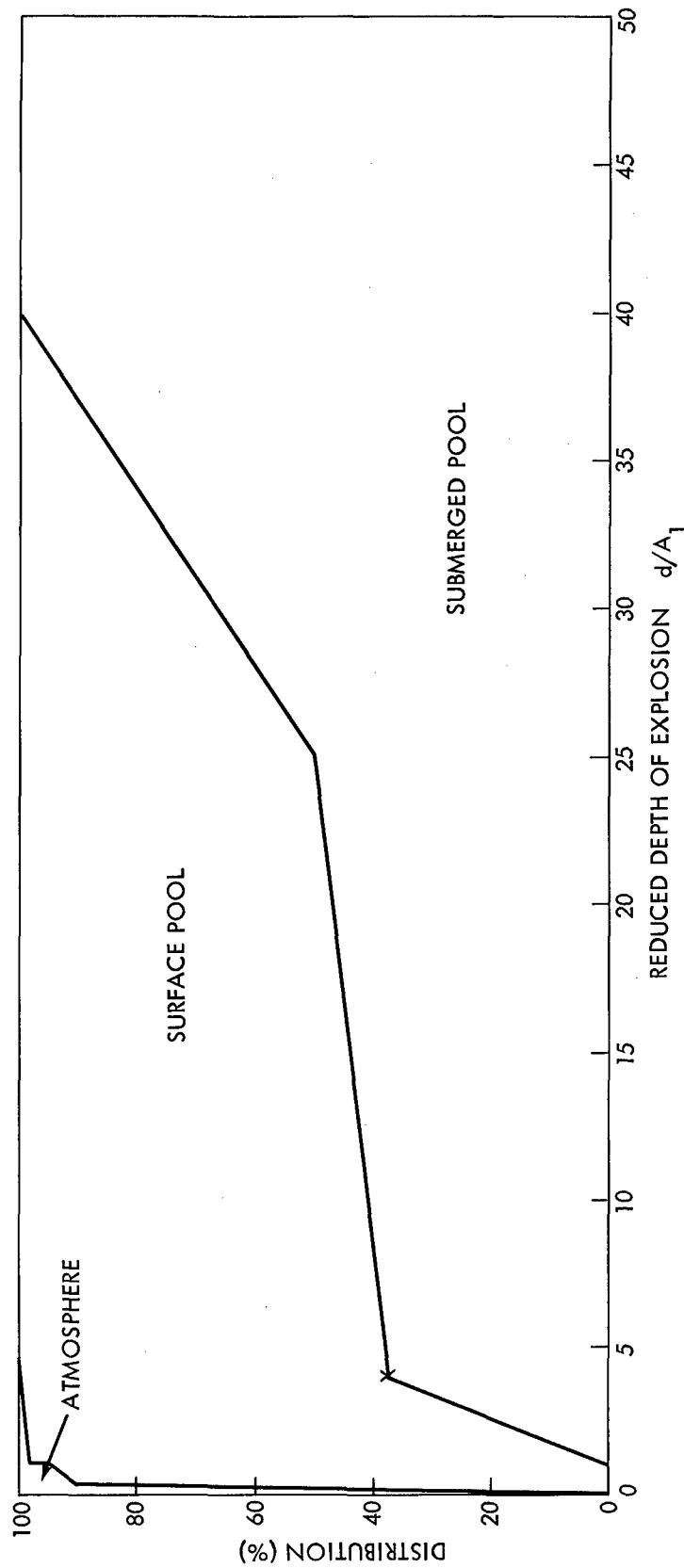


FIG. 2.16 ESTIMATED DISTRIBUTION OF SOLID PRODUCTS OF UNDERWATER EXPLOSIONS

TABLE 2.8
TNT PRODUCTS IN A SURFACE POOL

Product		Concentration (mg/l)	
Name	Symbol	Pool	Ocean
Carbon Dioxide	CO_2	0.215	0.631
Carbon Monoxide	CO	0.217	28.8×10^{-6}
Carbon	C	0.172	28
Nitrogen	N_2	0.145	14.3
Water	H_2O	0.113	—
Hydrogen	H_2	3.64×10^{-3}	—
Ammonia	NH_3	1.08×10^{-2}	—
Methane	CH_4	6.22×10^{-3}	40.9×10^{-6}
Hydrogen Cyanide	HCN	2.13×10^{-3}	—
Ethane	C_2H_6	4.44×10^{-4}	1.49×10^{-6}

place. The most conservative* theoretical models indicate that the maximum concentration over a long time period decreases with the square of the time. On this basis, the concentrations given in Table 2.8 may be reduced by the time squared to provide a rough estimate of long period effects. The values obtained will represent an upper limit.

The radius of the pool is also a significant parameter, but this becomes difficult to define and to measure at late times because of mixing at the edge. If the pool extent is defined as the radius at which a particular level of concentration is detected, this value will increase with time and then decrease as a result of dilution. However, as the horizontal variance** of the pool increases in proportion to $t^{2.54}$ (Pritchard, et al, 1971) it may be assumed that the radius increases roughly as $t^{1.27}$.

Strictly speaking, the concentration in a pool will always exceed background levels, because the explosion products are added to the constituents already in sea water. However, when the added substances become an order of magnitude below the background levels, it would seem realistic to consider them then to be a part of the environment. In most cases this occurs prior to the time of pool stabilization (see Table 2.8).

The possible hazardous levels of substances such as these in regard to marine organisms have not been well documented, but some estimates have been given for CO_2 , NH_3 , and HCN (FWPCA, 1968). The Federal Water Pollution Control Administration recommends that the free carbon dioxide concentration should not exceed 25 mg/l and offers evidence that the pH of the water has an important effect on the toxicity of cyanide and ammonia. Some undesirable effects were noted at hydrogen cyanide concentrations of about 0.3 mg/l and it was found that 2.5 mg/l of ammonia is acutely toxic. These values are well in excess of those calculated for the surface pool. Also, as indicated previously, the values given in Table 2.8 are doubtless unrealistically high.

2.3.3.3 Inland Waters. The explosion phenomena, up to the time of stabilization of the pools, are the same in inland waters as in the open sea. However, as indicated in Section 2.3.2.3, the background levels of dissolved substances can be substantially different. In addition, the transport and diffusion of surface and submerged pools will be controlled by local conditions. It is necessary, therefore, to study these in advance if predictions of the concentration of explosion products at relatively late times are needed.

In a typical estuary, three water layers may often be distinguished (Pritchard, et al, 1971). The surface layer has a low but roughly constant salinity, and the bottom layer has a higher salinity. In the intermediate layer, salinity increases rapidly with depth. The surface layer has a net motion seaward, while the bottom layer flows toward the head of the estuary. In addition,

* In this case, a conservative model is one that gives a high value of concentration, or pool size, at a given time.

** The mean squared value of the horizontal distance of explosion product parcels from the center of the pool.

a tidal oscillation is added to the circulation pattern, and vertical transfer across the intermediate layer may occur. The fate of a pool of explosion products in an estuary therefore is influenced by a variety of factors, including the initial depth of formation and the local currents and tides.

Currents and diffusion processes are also complex in the Great Lakes, where pronounced seasonal and diurnal variations have been found (e.g., Murthy, 1972; Csanady, 1972). In some locations, the currents can shift drastically in a few hours.

In a small pond, an accumulation of solid explosion products may occur over a period of time. This can be estimated from the weights of the charges and the rate of firing.

2.3.4 Bottom Effects

The most obvious effect of explosions on the seabed is cratering, and there is probably no doubt that benthic sea life in the cratered region will be destroyed. As a rule of thumb, the bottom is probably disturbed over twice the width of the crater. Figure 2.17 has been extracted from a report by Young (1971) to indicate the width and depth of craters on clay or sand bottoms. At greater scaled depths of explosion, experimental data are limited, but the following equation may be used to estimate crater width. This equation is based on the assumption that the crater radius is equal to the explosion bubble radius when the water is relatively deep.

$$C_w = 29 \frac{W^{1/3}}{Z^{1/3}} \quad , \quad d/W^{1/3} > 1.0, \quad (2.15)$$

where:

C_w = crater width, ft.

Crater effects are temporary on sand or mud bottoms, but a crater in clay may persist for a period of years. The restoration of benthic life probably takes up to a year in the vicinity of a crater.

The effects of a yielding bottom on an explosion bubble have not been investigated, but it is known that the bubble from a very deep explosion on a rigid bottom tends to pulsate at the bottom before it floats upward. An example of this type of behavior in a small-scale model test is shown in Figure 2.18.

It may be assumed as a rough guide that a pulsating bubble will remain at the bottom when the explosion depth exceeds the following:

$$d_b = 30W^{1/4} \quad , \quad (2.16)$$

where:

d_b = depth at which the bubble pulsates at the bottom, ft.

When the oscillations are completed, the remaining gas doubtless rises toward the surface, possibly as a cloud of small bubbles. It seems likely that a portion

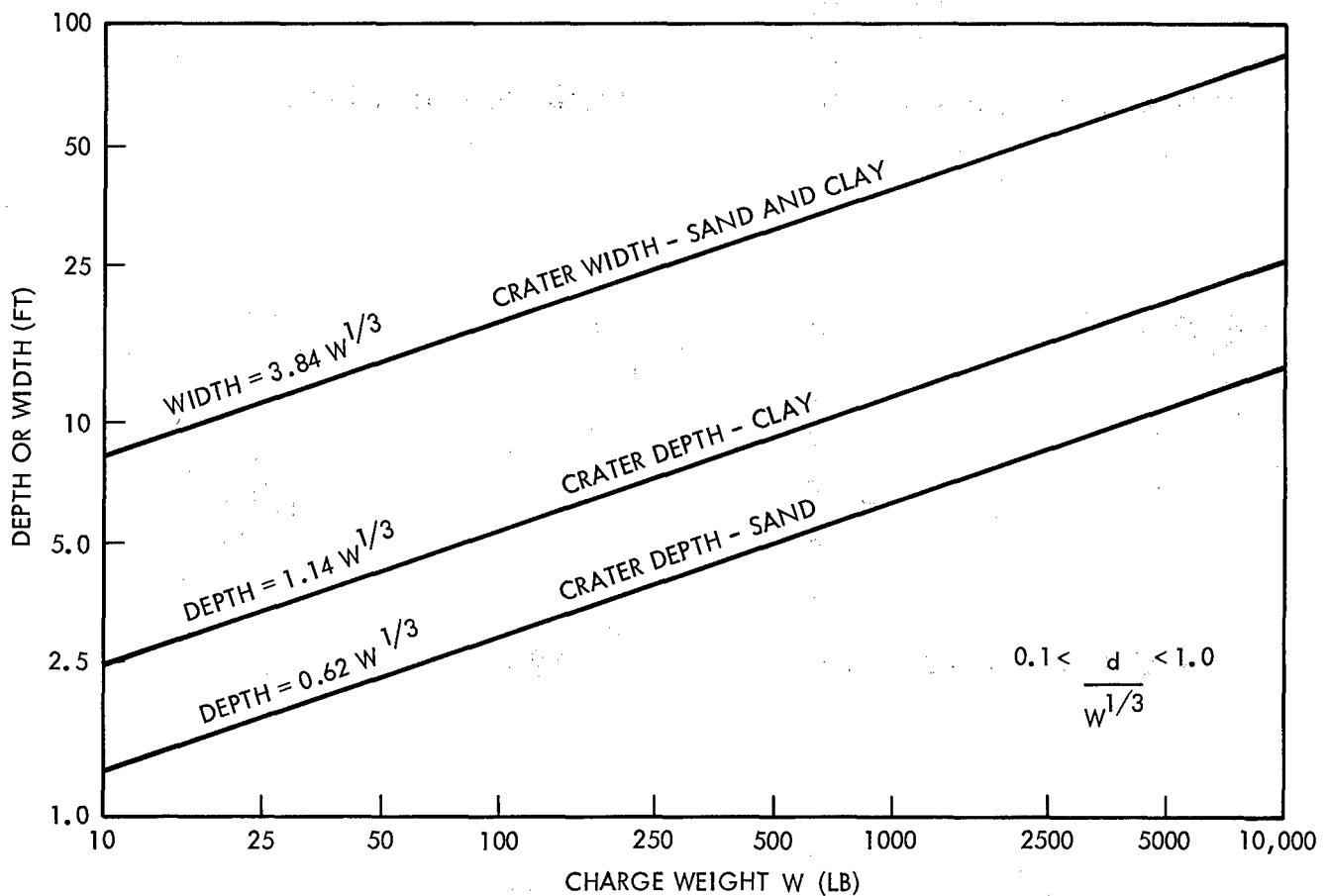


FIG. 2.17 UNDERWATER CRATER WIDTHS AND DEPTHS

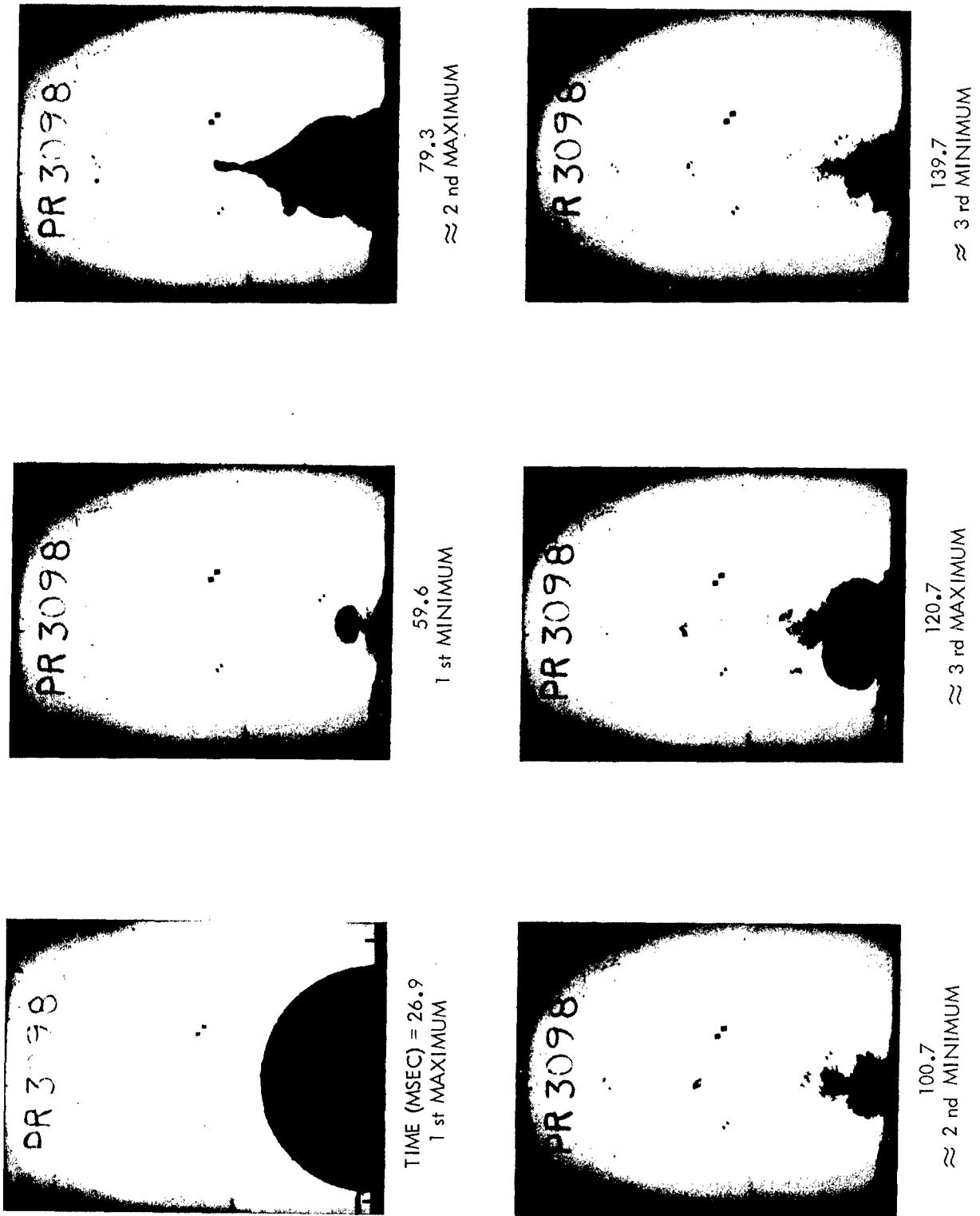


FIG. 2.18 BUBBLE PULSATING ON THE BOTTOM IN VACUUM TANK EXPERIMENT

of the solid products will remain in the crater and some of the finer bottom particles will be carried upward with the bubbles. It also seems likely that a turbidity cloud of disturbed bottom material will remain in the vicinity of the burst for some period of time. A secondary effect of interest is that an explosion on the bottom could possibly release a cloud of natural gases, such as methane, from the bottom sediments.

This problem has received little attention, but some guidance can be provided on the basis of existing relevant information. The amount of bottom material dislodged should be equal to the crater volume, as shown in Figure 2.19. At greater depths, the following equation may be utilized to provide an estimate:

$$C_v = 2360 \frac{W}{Z} \quad , \quad d/W^{1/3} > 1.0, \quad (2.17)$$

where:

$$C_v = \text{volume of crater, ft}^3.$$

This volume is an upper limit to the material that remains suspended for a significant period of time, as in certain types of bottom, such as clay, large clumps may be ejected. These ejecta fall back immediately.

As marine sediments are frequently classified by the size distribution of their particles, a knowledge of the sediment type can be used to provide an estimate as to whether a turbidity cloud and appreciable upward transport will occur. In Table 2.9, the size classifications are given; and as a general rule, particles larger than 1 mm in diameter can be expected to settle too rapidly to form a persistent cloud. However, particle size alone is not a sufficient criterion, as clay can have considerable cohesive strength. Turbidity clouds are therefore most likely over silt bottoms, or bottoms where the percentage of silt and clay is greater than fifty percent (Athearn, 1967).

As the properties of sediments and sediment clouds are not well understood, the values in Table 2.9 are only a rough guide. For example, a suspended particle will fall more slowly in turbulent water than in still water (Murray, 1970), but a dense cloud of sediment might settle at a faster rate than an individual particle (Young, 1965). However, in the latter case, the cloud would then spread out laterally.

On a practical basis, the presence of a deep cloud of sediment is probably of no concern. However, when explosions occur in shallow water, the displaced bottom material is clearly visible to observers and could result in complaints if it persists and is carried from the area by currents. In the case of TNT tests, for example, this material would be mixed with the carbon in the surface pool. Some downwind deposit would also occur from airborne material. It seems likely, however, that no bottom material would become airborne with explosion depths in excess of $1.0 W^{1/3}$ feet.

The possibility exists that the bottom mud might be contaminated and that these contaminants would be dislodged and redistributed by an explosion. However, this is probably a localized effect of only limited concern.

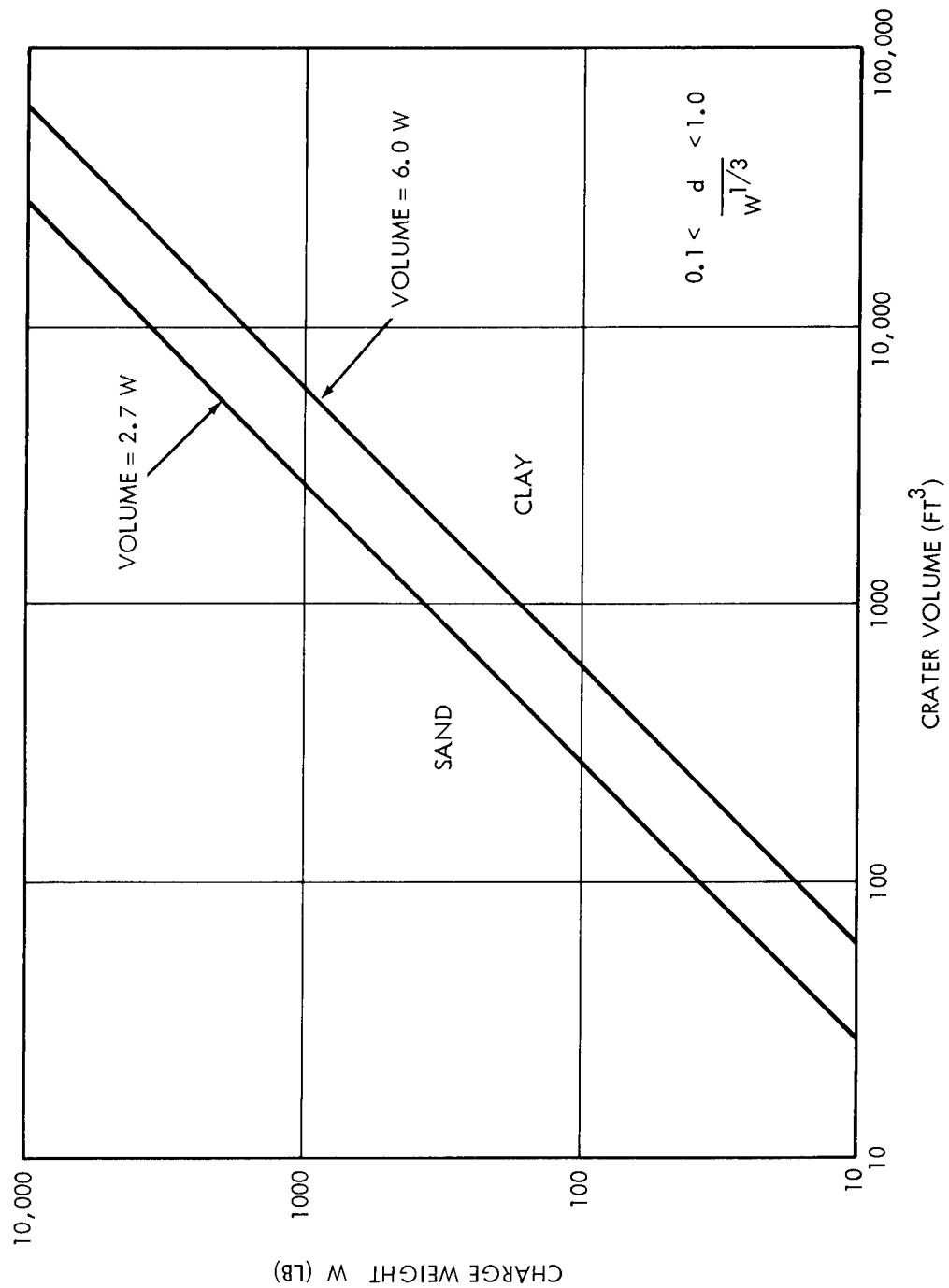


FIG. 2.19 CRATER VOLUMES

TABLE 2.9
PARTICLE SIZES IN MARINE SEDIMENTS

Category	Particle Diameter Range (mm)
Clay	0.000125 - 0.00195
Silt	0.00391 - 0.0312
Very Fine Sand	0.0625 - 0.125
Fine Sand	0.125 - 0.250
Medium Sand	0.250 - 0.500
Coarse Sand	0.50 - 1.0
Very Coarse Sand	1.0 - 2.0
Granules	2 - 4
Pebbles	4 - 64
Cobbles	64 - 256
Boulders	256 -

SOURCE: Sverdrup, et al (1946)

If an explosion takes place on or near a sloping bottom, consideration should be given to the possibility of initiating a turbidity current. This current is formed by a suspension of sedimentary particles that flows along the seabed because the bulk density of the mixture exceeds that of clear sea water. The motion starts on a sloping bottom, and the current then moves downslope and fans out a considerable distance across the sea floor because of its inertia and its low viscosity. Sand and silt are gradually deposited on the bottom as the current slows down and stops. The best documented example is the current that broke twelve telegraph cables on the seabed immediately after the 1929 Grand Banks earthquake (Heezen and Ewing, 1952). The epicentral area was on the continental slope, about 6000 feet deep, and the current evidently moved down the slope at a high velocity and halted somewhere on the ocean floor over 400 miles away at a depth of 17,000 feet. Cables on the Grand Banks were not disturbed.

Mud slides or slumps can also occur on sloping bottoms. These have a high density and can contain large particles or boulders in some cases. In general, they will come to an immediate stop when they reach the bottom of a slope (Kuenen, 1956).

An avalanche is a density flow on land that is similar in many respects to an underwater turbidity current. Explosives are commonly employed to check the stability of snow, and in some cases, to start an avalanche when it reaches a dangerous state (Forest Service, 1961). If the snow is stable, the explosive charge produces a crater, indicating that no avalanche hazard exists.

A similar condition possibly exists on the seabed; although some experiments conducted with explosives in unstable sediments in the Scripps Submarine Canyon off La Jolla, California produced craters instead of turbidity currents (Dill, 1966). It seems possible that the explosives were not placed in the positions needed to trigger a density current or that the sediments were not sufficiently unstable. As this general subject is not well understood, the generation of a current, or a slump, should be considered as a possible environmental effect of an explosion on a sloping bottom. This situation should be avoided, if at all possible, in Navy testing.

2.3.5 Sub-Bottom Effects

When an explosion occurs with a relatively slight burial of the charge, i.e., less than about $0.2 \text{ ft/lb}^{1/3}$, the effects will be similar to those of bottom shots. However, when charges are buried deeply in the bottom, the deposit of solid products within or on the bottom should be almost complete. As long as cratering occurs, gases will escape, though it is unlikely that a single large coherent bubble will be formed. Crater radius increases with depth of burial, to a value about double the radius of a bottom explosion crater when the reduced depth, below the bottom, is about $1.0 \text{ ft/lb}^{1/3}$. Containment within the bottom will possibly occur at a reduced depth of $5.0 \text{ ft/lb}^{1/3}$. As this problem has been given almost no attention in the past, these values are highly speculative.

A sub-bottom explosion will generate pressure and shear waves that will be partially reflected from the seabed and will be transmitted, in part, to the water. This complex problem has not been investigated except for studies related

to the possible environmental effects of deep underground nuclear tests in the Aleutians (Kirkwood and Fuller, 1971). The shock wave entering the water on the Cannikin test was estimated to produce an overpressure of about 100 psi at the seabed in most areas. Biological effects, if any, were probably limited to benthic organisms.

The possibility exists that a sub-bottom explosion in the vicinity of a sloping bottom could trigger a turbidity current in unstable sediments. This explosion geometry may be more effective for this purpose than a charge resting on the bottom (see Section 2.3.4).

2.4 FISH

2.4.1 Mechanisms of Injury

The research conducted on the mechanisms of fish-kill by underwater explosions has been relatively limited, although it is generally accepted that fish with swim bladders are more vulnerable than other species and that rupture of the swim bladder is a prime cause of death.

Much of the available data is statistical and is based on the observation of dead fish floating after an explosion test (see Section 5.1); however, in a few cases, specimens were placed in cages at known distances from charges fired for the specific purpose of observing the effects on marine life. Experiments of this type were reported by the Chesapeake Biological Laboratory in 1948. Oysters, crabs, trout, rock (striped bass), croaker, spot and menhaden were studied.

The results were somewhat erratic, possibly because the number of specimens varied considerably during the tests. In cases where fish were placed a given distance from a charge on only one test, the results have less significance than if fish were placed the same distance from several shots of the same type. Figure 2.20 shows some of the results reported when more than ten specimens were exposed at the same distance from charges weighing from 28 to 32 pounds. The percentage of deaths includes those killed outright and specimens that died from injuries. The results are consistent with those of Hubbs, et al (1960), who reported a lethal range of about 500 feet with 25-lb charges of commercial explosives for sardines and anchovies. In these tests, also, there was considerable unexplained variation in the results.

Bottom dwellers are affected less than fish because of a different physiology and because the shock wave decreases rapidly along the bottom when explosions take place on the bottom (e.g., Hubbs and Rechnitzer, 1952). Effects on benthic life will be discussed in Section 2.4.4.

It has been assumed, in many investigations of fish lethality, that the radii of certain levels of injury and deaths are related directly to the peak pressure in the shock wave. However, this could never be demonstrated clearly because of the limited quantity of data and the fact that many tests were conducted in the vicinity of the bottom or the water surface. The shocks were therefore complex in structure as a result of the interaction of direct and reflected waves (shock waves reflected from the surface become tension waves and reflections from the bottom are positive; however, the strength of the latter is strongly dependent on the bottom material).

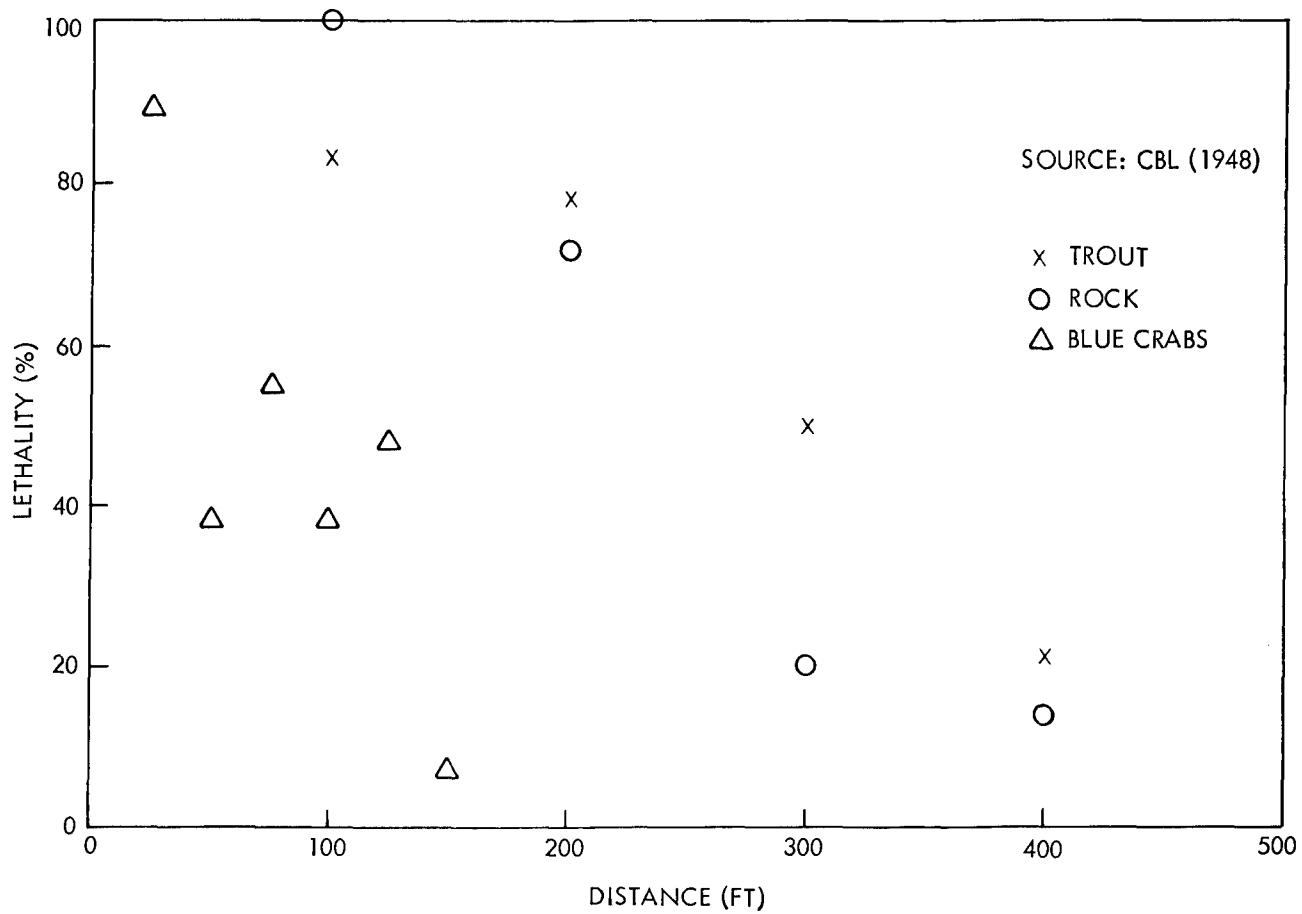


FIG. 2.20 LETHALITY DATA FOR MARINE LIFE FOR EXPLOSIVES WEIGHING 28 TO 32 POUNDS

The various contradictions in the data, plus experimental evidence and improved understanding of physiological processes lend support to the hypothesis that fish lethality is actually related to the negative pressures occurring in the water after the direct wave has been reflected from the surface. These negative pressures are found in an extensive region where the water is cavitated and in a zone beneath this region. The lateral extent of the region may not vary appreciably when different weight charges are used (Gaspin and Price, 1972).

Close-in fish will doubtless be killed directly by the strong shock wave, but in a relatively small volume of water. These fish have been observed to sink, rather than float to the surface.

Until a satisfactory theory of fish lethality is developed, statistical data on the weight or numbers of fish killed in experimental programs can be used for estimating the possible effect of planned tests. Such data for a single test have little value, but in some cases the number of tests was large enough to provide reliable averages for certain locations or seasons.

For example, Aplin (1947) reported observations of the fish killed in a series of 46 shots fired off the Southern California Coast in the Santa Barbara-Ventura Area during geophysical survey programs in 1946. Fitch and Young (1948) also collected data on fish killed as a result of geophysical survey work in the same general area during 1947. They published data for a total of 1296 shots. In both cases, the average charge weights were well under 100 pounds. No efforts were made to minimize the number of fish killed.

Coker and Hollis published data from larger (250 to 1200 lb) charges in 1950. Their data were obtained from 21 HBX-1 explosion tests conducted in the Chesapeake Bay during the summer of 1948. Most of the charges were fired near mid-depth in 150 feet of water. In this series, also, no effort was made to avoid fish-kill. In addition, statistical data are available on a continuous basis from 1958 for underwater explosion test programs conducted in the Chesapeake Bay and Patuxent River near Solomons, Maryland with techniques developed to keep fish-kill at a minimum level (see Section 5.1).

Most of the published values are in pounds of fish, rather than number, and this value is probably more meaningful in regard to market value. When the pounds of fish killed are reduced in terms of the weight of explosive, the ratios are fairly consistent. The data are presented in this form in Figure 2.21.

Because of the many variables involved, Figure 2.21 can be used only as a rough guide to possible fish mortality. However, it does show that fish-kill can be reduced in controlled programs. It is probably reasonable to assume that the average fish-kill can be held well below one-half pound per pound of explosive when precautions are taken (see Sections 5.1 and 6.2.1). This result would not apply to a single explosion, but to a series of tests in regions where the fish population is similar to that in the Chesapeake Bay.

Investigators of fish-kill have consistently reported that fish return to an area after explosions have occurred, i.e., there is no irreversible effect on fish population. In confined regions, such as submarine canyons, repopulation may require a few months after a period of testing (Hubbs and Rechnitzer, 1952).

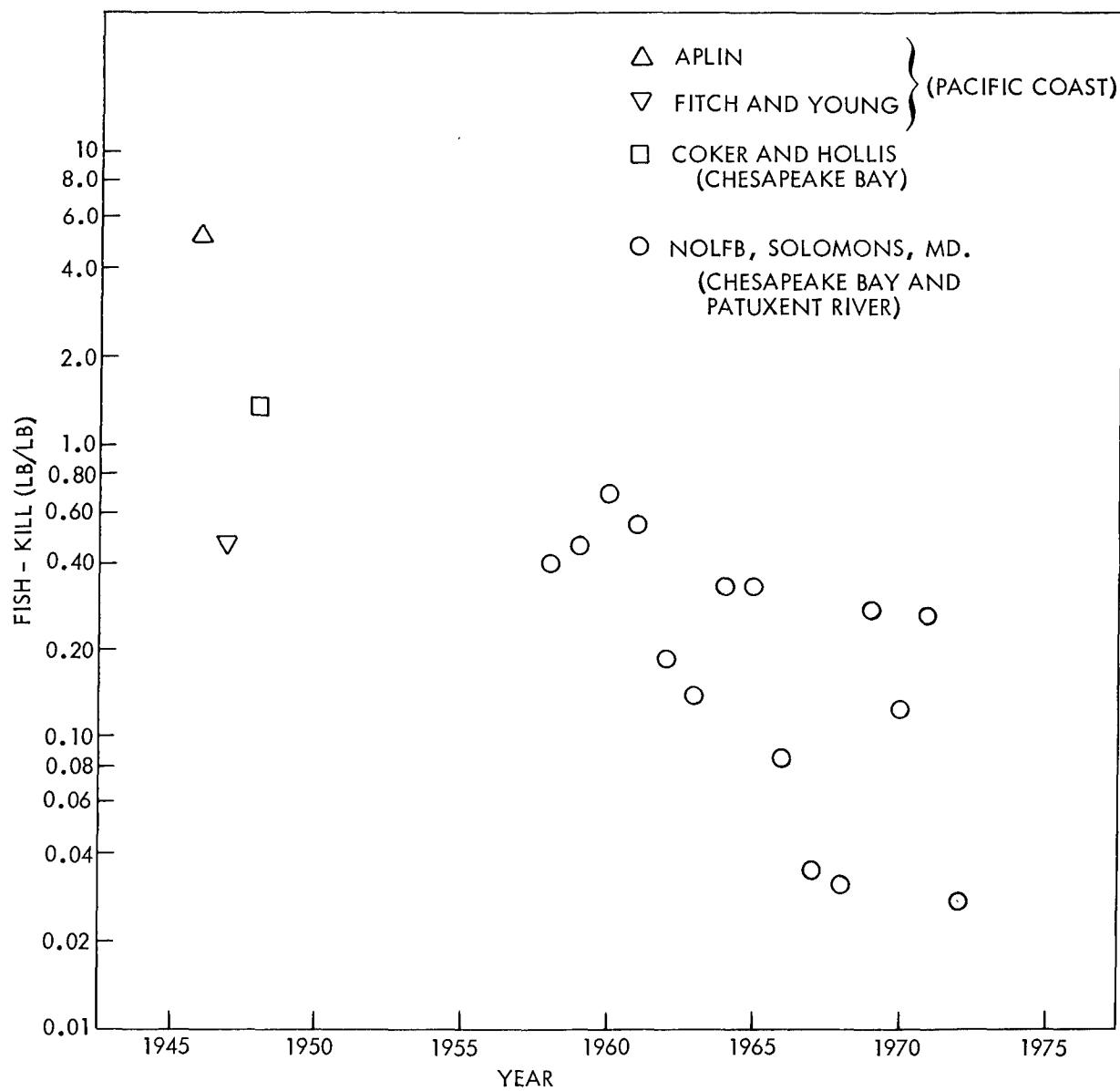


FIG. 2.21 STATISTICAL DATA ON FISH MORTALITY IN UNDERWATER EXPLOSION TESTS

2.4.2 Season

The seasonal trends in the availability of fish in the oceans and inland waters are well known to commercial fishermen and to sportsmen. These variations are probably more pronounced in inland waters than in the open sea. For example, the seasonal effects in the Chesapeake Bay and its tributaries are used as a guide for the scheduling of explosion tests (Section 5.1).

The most important fish in the Bay is the striped bass, which winters in water deeper than 40 feet because the cold waters retain a high oxygen content. Explosion tests are not conducted in the deep waters during the winter months for this reason, but tests in the same locations during the summer have a negligible effect on marketable fish.

Another seasonal influence to be considered is the local tourist season. For example, the busy season in the Florida Panhandle is during the summer months, while the main influx of tourists in south Florida occurs during the winter. The scheduling of tests during these periods is to be avoided, both from the point of view of safety and because of the possible objections of local Chambers of Commerce (see Section 5.5).

As it is beyond the scope of this report to cover all seasonal effects on fisheries, these should be investigated locally prior to the planning of tests.

2.4.3 Location and Depth of Burst

Most of the known commercial fishing grounds of the world are on the continental shelves and the banks of the oceans, generally in water less than 200 meters deep. The distribution of fish in other parts of the oceans is not well known, and the depths at which fish are found vary with the time of day and with other factors. For example, Backus, et al (1970), reported the results of about 290 midwater trawl hauls made to a depth of 1,000 meters in the equatorial and western North Atlantic Ocean from 1961 to 1968. The number of fish collected per hour in night-time collections in the North Atlantic Ocean showed maxima between depths of about 50 and 100 meters.

However, daytime hauls shallower than 200 meters caught little or nothing, partly because most mesopelagic species lie at greater depths by day. Many species migrate at sunset to depths shallower than 300 meters.

The possibility exists, then, that relatively deep explosions at sea could kill relatively large numbers of fish if measures are not taken to prevent this.

2.4.4 Bottom Explosions

There are probably benthic animals at all depths in the oceans, although the number decreases with increasing depth and is small at depths in excess of 2,000 meters (Wigley and Emery, 1967). The commercially important life, such as lobsters, crabs, oysters, and clams, is most prevalent in depths less than about 200 feet. Most of these are highly resistant to shock. For example, Aplin (1947) reported that lobsters showed no signs of injury from 20-lb charges fired at 50- and 55-foot distances.

In studies reported by the Chesapeake Biological Laboratory (1948), only 2% of oysters were killed at once and 5% died of injuries within 100 feet of 30-lb TNT charges and 200 feet of 300-lb TNT charges.

These results are mainly empirical, and no theory has been developed to provide a better understanding. However, it is evident that these benthic organisms are much more resistant to shock than fish with swim bladders. An additional contributing factor in some cases is the rapid attenuation of the underwater shock wave in shallow water and the even faster attenuation along the seabed.

2.5 SEA MAMMALS

Current information concerning the possible effects of explosions on sea mammals is extremely limited; however, the probability of killing a sea mammal in a test program is slight. The danger exists mainly on the Pacific coast, from California to Alaska. Operation Wigwam, for example, was conducted in a relatively barren area about 600 miles off the California coast, and there was some concern about the possibility of a whale encountering the submerged cables. There seems to be no doubt that the public concern over the inadvertent killing of a mammal would be greater than that usually expressed over fish-kills. This is evidenced by legislation to protect porpoises, seals, whales, and sea otters.

The possible effects of the Cannikin Underground Nuclear Detonation on all sea life, including sea otters, harbor seals, and sea lions were estimated prior to the test by Kirkwood and Fuller (1971). In their report, it was estimated that an overpressure of 100 psi or more could possibly rupture the eardrums of sea otters, leading to eventual death. In the case of a TNT explosion in free water, the range at which the 100 psi pressure contour is found is given by the following equation:

$$R_{100} = 116 W^{1/3} \quad , \quad (2.18)$$

where:

R_{100} = range of 100 psi overpressure level in free water, ft.

Kirkwood and Fuller made the following statement in regard to larger mammals: "It should be noted that studies on the relationship between body size (weight) and the response of an animal to atmospheric overpressure pulses suggest that as body size increases the tolerance to pressure pulses increases. Thus, animals such as harbor seals and sea lions, which are several times as large as sea otters, should be relatively less vulnerable to underwater overpressure pulses."

III

ADMINISTRATIVE REQUIREMENTS

3.1 REGULATIONS

3.1.1 Federal

Basic Federal laws, documents, and regulations pertaining to environmental effects in general include the following:

- A. Public Law 91-190, "National Environmental Policy Act of 1969," January 1, 1970.
Section 102 (2) (C) requires that a detailed environmental statement be included in "every recommendation or report on proposals for legislation and other major Federal actions significantly affecting the quality of the human environment."
- B. Executive Order 11507, "Prevention, Control, and Abatement of Air and Water Pollution at Federal Facilities," February 5, 1970, (35 Fed Reg 25, 2573 (1970)).
- C. Executive Order 11514, "Protection and Enhancement of Environmental Quality," March 7, 1970 (35 Fed Reg 46, 4247 (1970)).
- D. Public Law 91-604, "Clean Air Amendments of 1970," December 31, 1970.
- E. Executive Office of the President, Council on Environmental Quality, "Statements on Major Federal Actions Affecting the Environment," April 23, 1971 (36 Fed Reg 79, 7724 (1971)).

Contains guidelines for implementation of P.L. 91-190, i.e., the preparation of environmental statements. These include general guidance for determining when an environmental statement is required.

The Council on Environmental Quality (CEQ) was established to recommend a broad-ranging Federal program against pollution. Their findings are being published in a series of reports, e.g., "Ocean Dumping" and "Toxic Substances."

The Environmental Protection Agency (EPA) is an independent agency with five areas of responsibility: air pollution, water pollution, radiation health and safety, research on solid waste disposal, and control of dangerous toxicants in the environment. The EPA is basically an enforcement agency, but it also is responsible for setting standards, for anti-pollution planning, and for research and monitoring programs.

3.1.2 Department of Defense

Department of Defense Environmental Quality Policy encompasses many topics that are not related to explosion testing. Therefore, only documented items that are relevant in some manner to explosions will be included in this section and the remainder of this chapter. The emphasis will be on underwater tests; however, some aspects of land testing are also of interest.

It is the policy of the DOD that (OSD (H & E), 1972):

"Maximum effort will be made to incorporate environmental pollution preventive measures in the basic design for weapon systems, military materiel, and tests and exercises."

"Department of Defense components will cooperate fully with the Environmental Protection Agency and other Federal agencies, and will comply with such published standards and criteria relating to pollution abatement for Federal agencies as are promulgated by those agencies or by State and local agencies."

Department of Defense Directive Number 6050.1 of 9 August, 1971, establishes the DOD Environmental Policy in detail, stating initially that:

"At the earliest practicable stage in the planning process and in all instances prior to decision, the environmental consequences of any proposed action shall be assessed."

"Whenever an environmental assessment ... indicates ... that the resulting action may significantly affect the quality of the human environment or may be highly controversial with regard to environmental impact, a detailed environmental statement shall be prepared..."

As stated in Attachment 1 to Enclosure 1 of DOD Directive 6050.1, it is impossible to list all activities that would have a significant effect on the quality of the human environment; however, in a particular assessment, all environmental effects must be considered, whether those effects are adverse or beneficial. Examples of factors to be considered, as published in this document, are:

A. Effect on water.

Will the action:

- (1) Introduce toxic or hazardous substances or significant amounts of chemicals, organic substances or solid wastes into bodies of water,
- (2) Significantly increase sedimentation in a body of water, or
- (3) Significantly alter the temperature of a body of water?

Will the action improve the quality of a body of water?

B. Effect on atmosphere.

Will the action result in emissions into the atmosphere of toxic or hazardous substances or significant amounts of other pollutants?

Will the action result in the creation of excessive noise, considering the proximity of and the likely effects of the noise on humans or wildlife?

Will the action tend to reduce the amount of pollution in the atmosphere?

C. Effect on natural resources.

Will the action result in significant destruction of vegetation, wildlife, or marine life?

Will the action enhance the quality of vegetation, wildlife, or marine life?

Will the action significantly affect soil quality?

Will the action result in contamination or deterioration of food or food sources?

D. Other values.

Will the action significantly affect, beneficially or adversely, the health or welfare of man, including aesthetic considerations?

Will the action significantly affect, beneficially or adversely, other forms of life or ecosystems of which they are a part?

These factors all require consideration in the planning of underwater explosion tests, although the response to these questions will be largely negative.

3.1.3 Navy

Figure 3.1 is an abbreviated chart showing the Navy Environmental Protection Organization. A Deputy Under Secretary of the Navy for environmental matters has been established in the Office of the Secretary of the Navy to coordinate Navy and Marine Corps Programs. The Deputy Chief of Naval Operations (Logistics) has the principal responsibility for directing, coordinating, and monitoring the results of this program within the Navy. He also provides the Navy focal point for review of environmental impact statements. He maintains cognizance and purview over the issuance of authorizations and potential environmental effects of all target ship sinkings and deep water dumping operations.

The Chief of Naval Material also has broad responsibilities, including the following, as stated in OPNAVINST 6240.3B of 11 April 1972:

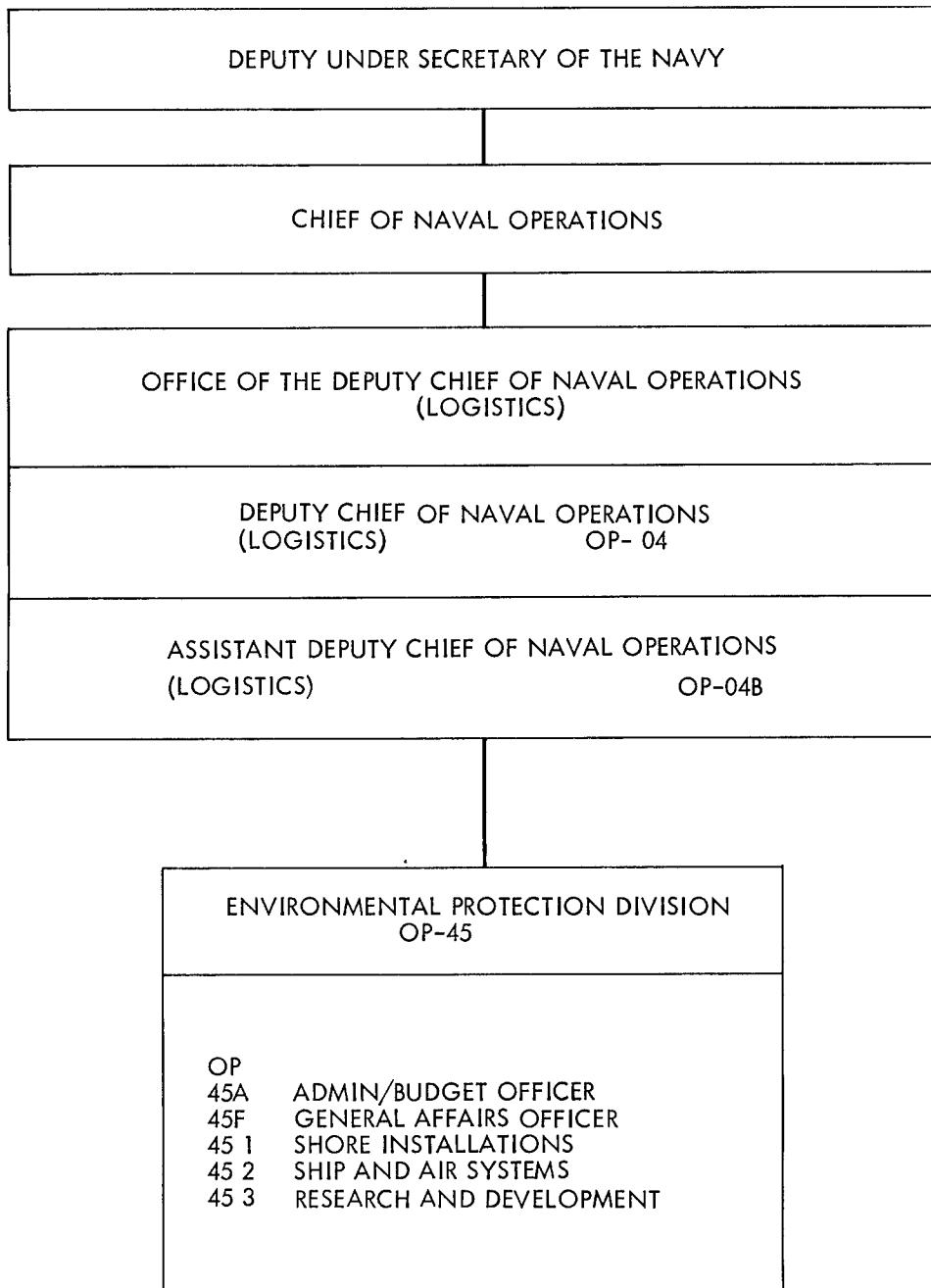


FIG. 3.1 NAVY ENVIRONMENTAL PROTECTION ORGANIZATION

- A. Identify and evaluate on a continuing basis activities and conditions affecting environmental quality, including but not limited to air and water pollution, solid waste management and disposal practices, noise, sources of thermal energy, ionizing and non-ionizing radiation, chemical agents, and biological research materials.
- B. Perform research to define and study environmental pollution problems associated with the fulfillment of Naval requirements, including those requirements associated with weapons systems, assuring that consideration is given to the control of environmental pollution through research, development, test and evaluation projects and programs, and the coordination of such research actions with other Navy commands, other Department of Defense components and Federal agencies.

OPNAV INSTRUCTION 6240.2A of 11 December 1970 reiterated the DOD policy requiring the assessment of the probable ecological and environmental consequences of an action at its inception. The list of the types of actions to be assessed included programs for weapons testing and programs for the large scale disposal of conventional ammunition. A five-point environmental impact statement (see Section 3.3) is required if the assessment indicates a significant adverse environmental effect or if the proposed action is likely to controversial. The decision to prepare a statement evidently rests with the originator, however, CNO (OP-45) will assist in the resolution of doubtful cases.

The following procedures for processing environmental impact statements have been extracted from OPNAVINST 6240.2A. (Procedures in regard to legislative proposals and real estate acquisition are not included because of their lack of relevance.)

- a. The cognizant Office, Command, or Activity prepares a draft environmental statement and submits six copies to CNO* via the chain of command.
- b. CNO coordinates the draft statement with other appropriate Navy components and advises originator of concurrence or non-concurrence.
- c. If concurrence applies, CNO submits copies of the statement to OASD (H & E)**.
- d. If CNO does not concur with the statement, the draft together with the recommended changes, will be returned to originator.
- e. The OASD (H & E), after review and coordination of the statement with other DOD components, advises CNO of concurrence, or recommends changes.
- f. Following receipt of OASD (H & E) concurrence or recommendations for revision, CNO directs the originator to resubmit 13 copies of the draft or revised draft statement to CNO. To expedite, the originator, unless otherwise directed, may forward copies directly to CNO with copies to the chain of command.

* OP-45

** Office of the Assistant Secretary of Defense (Health and Environment)

- g. Upon receipt of the draft statements by CNO, CNO submits 10 copies to the Council on Environmental Quality. CNO will concurrently request the originator to solicit the views of other federal agencies having jurisdiction by law or special expertise with any of the environmental problems associated with the proposed action, and to solicit comments from the state and local agencies when the environmental impact of the proposed action is pertinent to those agencies.
- h. After review of the comments and views received from federal, state, and local agencies, the originator shall forward 10 copies of the final environmental statement, including 10 copies of all comments received during the review process, to CNO for review and forwarding to the Council on Environmental Quality, and concurrently one copy of same to OASD (H & E).

It is important that draft environmental statements be prepared and circulated for comment and furnished to the CEQ early enough in the review process before an action is taken in order to permit meaningful consideration of the environmental issues involved. To the maximum extent practicable no administrative action shall be taken sooner than 90 days after a draft environmental statement has been circulated for comment and furnished to the CEQ, and, except where advance public disclosure will result in significantly increased costs of procurement, made available to the public. Neither shall such administrative action be taken sooner than 30 days after the final text of the environmental statement (together with comments) has been made available to the CEQ and the public. Consequently, the minimum waiting period after submission of the draft statement is 90 days because the 30-day period and 90-day period may run concurrently to the extent that they overlap.

It is interesting to note that Admiral Zumwalt, Chief of Naval Operations, issued Z-gram 114 on 6 July, 1972 to launch a test program of "Ecology Spotreps" (Spot Reports) by Navy ships and aircraft to report environmental hazards found at sea. The reports are designed to provide effective data on such environmental blights as oil spills, air pollution, accumulations of debris and fish kills, and includes observation in all areas on, above, and under the seas. This new Spotrep Test Program considers the collection of specific data on polluting effects in the world's oceans as an essential first step in eventual worldwide control of environmental hazards to the seas.

3.1.4 State

The legal aspects of underwater explosion testing in the Maryland portion of Chesapeake Bay have been well documented. A memorandum prepared by the Office of the Judge Advocate General to state the Navy's legal position in Maryland waters is reproduced in entirety as Appendix A. Certain items, which are believed to have validity in all states, have been extracted and condensed here.

In brief, constitutional authority for ordnance testing involving underwater explosions exists by virtue of the war powers of the United States. The right and power of regulation and control of navigable waters for purposes of national defense exists in peacetime as well as in time of war, for the power to wage war embraces the power to prepare for it. Tests and training involving underwater explosions are directly related to preparing for the defense of the nation.

The State of Maryland has a statute that prohibits placing, throwing, or using explosives in Maryland waters except for bona fide engineering, milling, or mining purposes. This does not bar the Navy from conducting explosive tests because the United States is not subject to the police power of the states. However, the authority of the Navy to conduct underwater tests is limited by the United States Code in that the tests shall not interfere unreasonably with the food fishing industry. If such interference occurs, the United States is subject to liability for resulting damage.

In addition, the State has legal means of halting explosion testing because, prior to the commencement of the tests, a permit must be obtained from the Army Corps of Engineers. If the State can show that the Navy is violating a state law, or is interfering with the food fishing industry, it can move to block the issuance of a permit or have a permit revoked. The Corps must therefore review all requests with this in mind and must consult the concerned agencies before issuing a permit.

3.2 DUMPING

3.2.1 Targets and Debris

There are at least two opposing points of view in regard to the desirability of dumping solid waste materials at sea. Sport fishermen, in general, are in favor of certain types of dumping for the creation of artificial fishing reefs, while many environmentalists oppose ocean dumping of all kinds.

The construction of fishing reefs has become an accepted practice on the Atlantic coast and in the Gulf of Mexico, and research in this field is being supported by the National Oceanic and Atmospheric Administration (Stone, 1971). The reason for this effort is that most of the continental shelf is relatively smooth and sandy and is lacking in natural reefs and rock outcrops that could provide a habitat for encrusting organisms such as barnacles, hydrooids, corals, and mussels, and also become protective areas, food sources, or spawning grounds for fish.

Artificial reefs can, in some cases, be more effective than natural reefs in attracting fish. Sunken ships are known to serve as artificial reefs, but materials such as concrete blocks, building rubble, automobile bodies, and scrap tires have been used successfully (Stone, 1971). The materials must, of course, be non-toxic solid wastes.

In some cases, obsolete ships may be deliberately sunk for this purpose (e.g., Ocean Industry, 1968; Burchard, 1972), and during 1972, target vessels employed in a Navy damage study were purposely sunk at a location near Key West, Florida, where a fishing reef was desired (see Section 5.2).

At the present time, it is assumed that this approach increases the fish population and is non-polluting. To investigate this further, the Naval Undersea Center has used the CURV to photograph two submarines sunk in 150 and 1,488 feet of water to check for possible changes in the biota (Cooke and Hoyt, 1971). It was found that the submarine at a depth of 150 feet gave every evidence of producing an artificial reef while the deeper submarine showed no evidence of colonization by sea life. Very slow changes are anticipated at this depth.

It is likely that an accidental sinking could cause considerable local pollution as a result of leakage of oil or other substances. However, a ship that is deliberately sunk should be cleaned of pollutants in advance. The water depth should be sufficient to preclude any hazard to navigation.

It is not advisable to dump garbage and other trash at sea when vessels are anchored, even though they may be several miles from land, as the debris from a stationary ship may remain in the vicinity or be carried to shore by the currents. In this regard, OPNAVINST 6240.3B states: "Garbage shall not be thrown overboard within the contiguous zone which is 12 miles from the coastline. All trash and rubbish disposed at sea should be packaged to have negative buoyancy."

It should be pointed out, however, that the latter is not necessarily the most desirable procedure. For example, when ordinary garbage is dumped from a moving vessel, a rapid dispersion occurs in the wake, and the garbage may serve as food for sea animals. In any event, it is biodegradable. On the other hand, packaged waste, if in plastic or metal containers, may persist for centuries.

It is of interest to point out here that the Department of the Navy prepared a Final Environmental Impact Statement on the Use of Target-Ship Hulls in Exercises at Sea in August 1971. The Statement is concerned with the use of ships as targets for conventional air-to-surface and surface-to-surface weapons during fleet exercises for the purposes of combat readiness training and weapons evaluation. Of necessity, these exercises are conducted at locations in excess of 50 nautical miles from any coast line and clear of all shipping lanes. The ships are sunk in water with a depth of at least 6,000 feet.

It was concluded that damage to marine life is minimal, but that contamination from petroleum products in the hulls could be a problem. However, the target ship tanks and lines are flushed with water, leaving a possible residue of four to five hundred gallons, at a cost between \$1500 and \$2000. Removal of the remainder would cost about \$22,000 and require about three weeks of additional preparation. The latter was not recommended, as it was felt that the few hundred gallons of residual fuel would be released slowly and would not constitute an adverse environmental effect on a long term basis.

The basic argument against the deliberate sinking of ships in deep water is that any part of the ocean floor is susceptible to eventual exploitation when the technology reaches the requisite state of development. The ships could then be a nuisance and a possible hazard. However, if deep parts of the ocean with limited marine resources are utilized, this possibility is minimized. An example is the use of the Blake Basin Disposal Site, where the water depth exceeds 16,000 feet, as an explosives dumping area (NAVRECONTECHSUPPCEN, 1971).

The report on Ocean Dumping prepared by the Council on Environmental Quality (CEQ) in 1970 states that: "Current regulatory activities and authorities are not adequate to handle the problem of ocean dumping." The report makes the following recommendations with direct or indirect application to explosive testing at sea or in estuaries:

High priority should be given to protecting those portions of the marine environment which are biologically most active, namely the estuaries and the shallow, nearshore areas in which many marine organisms breed or spawn.

Ocean dumping of existing sources of solid waste should be stopped as soon as possible.

Ocean disposal of explosive munitions should be terminated as soon as possible.

Use of waste materials to rehabilitate or enhance the marine environment, as opposed to activities primarily aimed at waste disposal, should be conducted under controlled conditions.

The last statement has relevance to the use of target vessels and other materials to create fishing reefs. The report of the CEQ also contains the following remarks, which tend to support this practice: "Construction and demolition debris, less than one percent of all wastes dumped in the ocean, are composed mainly of dense and inert materials. Because of the small amounts dumped and their character, these wastes are not a threat to the marine environment."

3.2.2 Oil

The Navy is particularly concerned with pollution of the sea and inland waters by the accidental or deliberate spilling of oil products (OPNAVINST 6240.3B). Even a relatively small discharge of oil can have serious effects on marine life and waterfowl, can contaminate beaches, and can cause risk of fire. This is relevant to experimental vessels at a test site and to the possible leakage of oil from a target vessel, either afloat or submerged.

The current presidential goal is to terminate all intentional discharges of oil and oily wastes into the oceans by 1975 if possible. Facilities aboard ships to hold oily wastes and sludges will be matched by facilities ashore to receive, process, and dispose of such wastes. At present, it is the policy of the United States that there should be no discharges of oil into or upon the navigable waters of the United States, adjoining shorelines, or into or upon the waters of the contiguous zone. The discharge of oil in harmful quantities in these waters is prohibited.

A National Contingency Plan has been prepared by the Council on Environmental Quality for coordinating the response to a spill of oil or other hazardous material. In the case of an accidental oil spill during a Navy explosion test program, an On-Scene Commander would be designated to take charge of oil containment and countermeasures, cleanup and disposal of the pollutants, and the restoration of the environment to its previous condition. The latter is relevant mainly to the contamination of a beach or shore-line.

3.2.3 Explosives

Millions of tons of unexploded ordnance have accumulated on the seabed during the past 100 years (Busby, et al, 1968). Most of the weapons dropped during wartime combat operations are in relatively shallow water, but obsolete ordnance that has been deliberately dumped at sea is usually in water at least 6,000 feet deep.

The CHASE program consisted of at least 16 shiploads of obsolete and unserviceable munitions that were sunk at disposal sites in the Atlantic and Pacific. Of these, 12 exploded, either deliberately or accidentally, while sinking; and the remainder went to the bottom intact. At the present time, all deep water dumping of obsolete munitions has been suspended pending a study of all alternative methods of disposal, particularly methods that will have a minimal impact on the environment.

However, if explosive dumping takes place at sea, detonation is preferable to sinking, because a controlled explosion is not hazardous to human life, while a sunken ship loaded with explosives is a hazard for an indefinite period of time. In addition, a depth of explosion can be selected that will minimize undesirable environmental effects.

The fragments and debris from five exploded CHASE ships covered areas of the seabed averaging about 500 meters in diameter (Spiess and Sanders, 1971). Photographs showed many benthic organisms in the debris fields, with no evidence of irreversible damage.

3.3 ENVIRONMENTAL IMPACT STATEMENT

An environmental impact statement should include a description of the proposed action and tell why it must be accomplished. In addition, a detailed schedule is needed. The following five essential items belong in the body of the statement, as set forth in OPNAV INSTRUCTION 6240.2A of 11 December 1970:

- a. Predictions of the probable total impact of the proposed action on the environment. This shall include commentary of the direct impact on some part of the environment such as the clearing of the forests or the pollution of air or water resources, as well as the more threatening danger associated with changes in existing eco-systems. Indirect or secondary significant consequences for the environment should be included for the analysis. Likewise, any benefits to the environment resulting from the proposed action shall be mentioned.
- b. A statement of any adverse environmental effects which cannot be avoided should the proposal be implemented. This would include an evaluation of the extent to which aesthetically or culturally valuable surroundings, human health, high standards of living, and other of life's amenities would be sacrificed.
- c. A list of carefully developed alternatives to the proposed action that might avoid some or all of the adverse environmental effects. Include with these alternatives economic, technical, and operational considerations, as well as their environmental impact.
- d. A detailed description of the relationship between local short-term uses of the environment and the maintenance and enhancement of long-term productivity. For this exposition, assessment of the action's cumulative and long-term effects is required. Short-term uses are to be construed as those not affecting succeeding generations.

- e. An inventory of all irreversible and irretrievable commitments of natural resources which would be involved if the proposed action should be implemented. This section should identify the extent to which the action curtails beneficial uses of the environment.

Environmental impact statements should be comprehensive and precise, and should contain thorough documentation when this is available. As the statements must be made available to the public when possible, it should be assumed that they will receive careful scrutiny. In addition, environmental action groups, special interest associations, governmental agencies, and Congressional Committees may be expected to use the environmental impact statements as a source of information.

The environmental statement should be accompanied by a summary sheet that must provide the following information:

- A. Indicate whether the statement is draft or final.
- B. Give the name of the action and indicate whether it is an administrative or legislative action.
- C. Provide a brief description of the action and indicate what geographical region (States and counties) is particularly affected.
- D. Summarize the environmental impact and adverse environmental effects.
- E. List alternatives considered.
- F. (For draft statements) List all Federal, State, and local agencies from which comments have been requested.
- G. (For final statements) List all Federal, State, and local agencies and other sources from which written comments have been received.
- H. Provide the dates the draft statement and final statement were made available to the CEQ and the public.

IV

EXPERIMENTAL MEASUREMENTS

4.1 MONITORING A TEST4.1.1 Fish Counts

Although it has become a standard Navy procedure to take all feasible measures to prevent the killing of fish in underwater explosion testing, this is sometimes unavoidable and dead fish are observed at the surface. In some cases, the number and species of fish killed are estimated visually. However, a preferable method is to net the dead fish and remove them from the site to avoid the possibility of the carcasses drifting to shore. The dead fish should be sorted and counted or weighed.

As game fish killed by an explosion remain edible, they can be cooked and eaten. On the other hand, if large numbers of trash fish are killed, they may be ground up for use as bait or dropped back in the sea as food for other species. In terms of ecology, the latter is probably the best procedure.

Fish counts of this nature should not be expected to provide biological effects information, though a visual estimate of the lethal range can be made. The actual location and number of fish killed will depend on the pre-shot fish distribution, which will doubtless not be uniform.

4.1.2 Water Sampling

Various techniques have been developed by oceanographers for sampling the waters of the seas at various depths. These include, for example, the Nansen bottle, the Niskin bottle, and the Van Dorn Sampler. However, sampling of the sub-surface water affected by an explosion would require accurate placement and control of sampling devices and would also involve an appreciable number of stations to insure success. Even so, it would be necessary to employ a sensitive tracer to provide assurance that a sample was, in reality, affected by the explosion.

For monitoring purposes, the simplest and least expensive technique is to use a fluorescent dye tracer and then sample the surface pool by traversing it with a small boat. A container of fluorescein dye, mixed with water, can be attached to the supporting cable directly above the charge. A ratio of one lb of dye to 100 lb of explosive should provide visibility for at least one-half hour. The sampling containers can be one-liter plastic bottles, providing that the bottles can be sealed tightly, preferably with O-rings. The times and locations of sampling should be recorded for a total time of one-half hour.

Water samples can be analyzed for virtually any constituent by currently available techniques, such as the use of a mass spectrometer. The data can be extrapolated by diffusion theory, such as described in Section 2.3.3.2, to estimate concentrations at late times. An alternate approach is to measure the concentration of dye with a fluorometer, either *in situ* or in sampling bottles, as the concentration of dye is proportional to the concentration of explosion products. However, this method is less precise than the direct measurement of explosion products.

Dye concentration can also be determined from an aerial photographic negative with a photodensitometer (Ichiye and Plutchak, 1966). This method has the advantage of providing data for the entire surface pool at selected times.

As fluorescein dye is used as a distress signal by downed pilots, local Naval Air Stations should be notified in advance if it is to be used in an explosion test. It should be noted that the dye dissolves to a low concentration within minutes and that it is harmless to man and to sea life. Although it has the property of high visibility at low concentrations, it will not color a submerged object and leaves no mark.

Fluorescent dyes are used frequently by oceanographers for the study of diffusion processes and as tracers for sewage and other pollutants. They do not have the undesirable features of radioactive tracers, which have been used in the past, because extremely low concentrations of radioactive materials are detectable.

The dye most frequently used by oceanographers is rhodamine, a red fluorescent dye (e.g., Katz, et al, 1965). However, when this was used in underwater explosion tests, the dye remained visible for only a few minutes. This was possibly a result of a partial decomposition of the dye by the heat of explosion. Other dyes have also been tested, but none proved to be as satisfactory as fluorescein.

4.1.3 Temperature Measurement

As theory and experimental data both indicate clearly that temperature changes produced in water by explosions are entirely negligible after a few minutes have elapsed, there seems to be no justification for attempting to measure this effect for the purpose of monitoring a test. However, if a need does exist, two approaches are feasible. One is simply to traverse the pool (made visible by a fluorescein dye tracer) with a small boat, utilizing a thermistor at the end of a probe held at the bow. The thermistor should be at least one foot deep. A battery-powered chart recorder may be operated in the boat. An accurate, fast-responding system is needed, as temperature changes of only a few tenths of a degree should be anticipated.

An alternate approach is the use of infra-red equipment in a low-flying aircraft to scan the surface pool. Many such devices are available commercially, and this technique is now commonly employed in studies of thermal pollution and other environmental effects (e.g., Burnett and White, 1970).

4.2 ACQUISITION OF BASIC DATA

It must be recognized that efforts to monitor a Navy test, or to acquire environmental data from a series designed for a different purpose, will produce

only qualitative results. It would probably not be feasible to expend the effort to acquire extensive quantitative data as an adjunct to such tests. In some cases it would hamper and delay progress toward the primary objective; in others it would provide data that is unique because of the test configuration* and is therefore limited in its usefulness.

As a general rule, it is extremely difficult to collect accurate data on the environmental effects of underwater explosions. When done properly this entails the careful underwater placement of sensitive sensors and sampling devices in a three-dimensional array. The measured effects will be highly variable in space and time and will often be difficult to distinguish from natural events. The records will be difficult to interpret unless underwater photography and dye tracers are employed.

Underwater photography is not feasible unless relatively small explosive charges are used. In any case, above-surface photography is a primary source of data, and extensive coverage is essential. This must be handled in such a manner that accurate timing and length scale markers are recorded on the films.

The number of fish killed in most underwater tests is highly subject to chance and cannot be used for prediction purposes except on a statistical basis. Data useful for evaluating biological effects can only be acquired in controlled tests with fish placed in cages at selected positions and detailed pressure-time records obtained at the same locations. Other specimens should be placed in the same type of cages at the same depths for the same periods of time, as controls, to evaluate possible effects of confinement.

* An example of this type might be an explosive charge fired a few feet from a very large target, possibly injecting gaseous products into the target.

CASE HISTORIES

5.1 NAVAL ORDNANCE LABORATORY FIELD BRANCH - SOLOMONS, MD.

Explosive tests of underwater ordnance have been conducted near Solomons, Md., since 1944 (Green and Davidson, 1969). These include tests with mines, torpedoes, depth charges, and other explosive actuated devices, as well as research on the phenomenology of new or special explosives. Four explosive firing sites are in use; three in the Patuxent River and one in the Chesapeake Bay. The locations of these are shown in Figure 5.1.

Procedures have been developed over a period of years to minimize the harmful effects of the explosions on fish and other marine life. These methods have been evolved in cooperation with the State of Maryland Department of Natural Resources and the Chesapeake Biological Laboratory at Solomons. The latter is a branch of the Natural Resources Institute of the University of Maryland. In brief, the procedures are the following:

A. Firing is not permitted during certain months and at certain depths where high concentrations of fish are expected. Oyster bars are avoided.

B. The State of Maryland (Department of Natural Resources) is notified by telephone and telegram prior to each test.

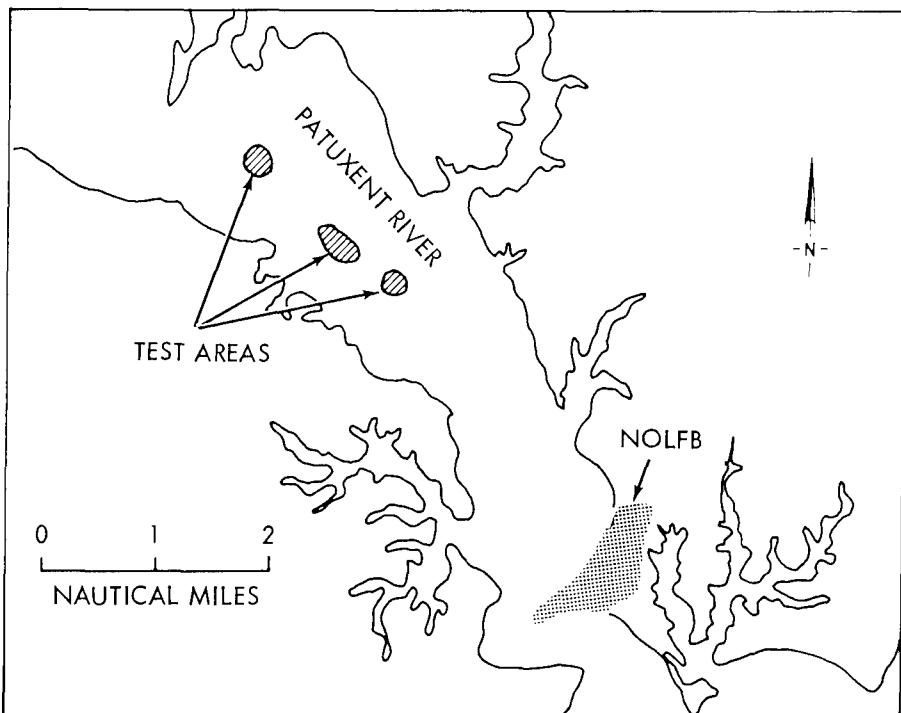
C. Observers from the State of Maryland are invited to all tests.

D. Fish-finders (special fathometers) are utilized to detect fish in the vicinity of the site. If appreciable numbers are observed, the test is delayed.

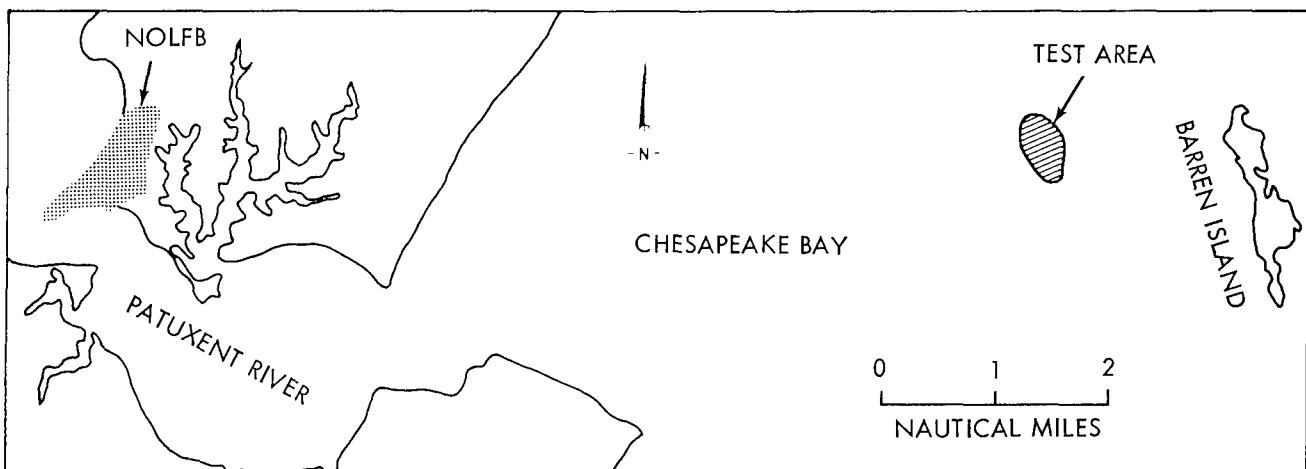
E. Dead fish are netted after each shot and estimates of the weight and species are made.

F. The dead fish are sometimes ground and are dropped as food for crabs or other fish.

The firing programs are geared to the ecology of the river and bay with a view toward the elimination of any harmful or irreversible effects. No firing is done in areas known to be favored habitats of fish. In general, firing is permitted in the Patuxent River during the entire year in water depths down to 40 feet. Firing is permitted at all depths from April through November. No firing is permitted at the Chesapeake Bay site during December, January, and February; and, in some years, during March. The reasons for these requirements are given in Table 5.1, as developed by the Chesapeake Biological Laboratory. In special circumstances the rules may be modified. For example, no firing was permitted in the Patuxent River during the latter part of 1972 because of the harmful effects of abnormally heavy rainfall on oyster production.



A. PATUXENT RIVER SITES



B. CHESAPEAKE BAY SITE

FIG. 5.1 EXPLOSIVE TEST AREAS USED BY NOLFB, SOLOMONS, MD.

TABLE 5.1
ESTIMATED EFFECTS OF UNDERWATER EXPLOSION TESTS ON MARINE LIFE
IN THE PATUXENT RIVER AND CHESAPEAKE BAY

Degree of Damage to fish*	Types of Fish in Designated Areas	
	Chesapeake Bay Depths Greater than 40 feet	Tributary Rivers Depths Greater than 40 feet
1. Maximum prob- able damage December, Jan- uary, February	Maximal concentration of striped bass occurs near the bottom in deep water. There is a high probability that large kills of striped bass will result. Some white perch and juveniles of other species will be killed.	Maximal concentration of white perch occurs near the bottom in deep water. There is a high probability that large kills of white perch will result. Some striped bass will be killed.
2. Heavy probable damage November and March	Since striped bass and large white perch are migrating into deep oxygen-rich water in late fall and early spring, large kills may result among striped bass; few white perch will be killed.	Some striped bass concentrate in deep water of lower estuaries and most white perch concentrate in the same areas. Large numbers of white perch and some striped bass will be killed.
3. Moderate prob- able damage April, May, September, October	Migratory fishes, including striped bass, shad, river herrings, white perch, etc., will appear in kills. Schooling surface fish may be killed.	Same as open Bay.
4. Least probable damage June, July, August	Since most fish do not fre- quent deep oxygen-poor waters, few marketable fish will be killed. Menhaden will be killed in large numbers. Schooling near-surface striped bass and other species may be killed at times.	Same as open Bay.

* Assuming no efforts are made to avoid fish-kill.

SOURCE: ltr from L. Eugene Cronin, Director of Maryland State Board of Natural Resources to Commander, NOL, 10 January 1957.

Statistical data on the weights of explosive fired and on the weight of fish killed are available on a regular basis from 1958. These values provide guidance concerning the average effects of an extensive controlled firing program. The data are summarized in Table 5.2.

It is interesting to note that personnel of the Chesapeake Biological Laboratory and the U. S. Fish and Wildlife Service observed the results of 21 HBX-1 explosion tests in the deep water firing site in the Bay during the summer of 1948 (Coker and Hollis, 1950). This was prior to the initiation of the measures taken to minimize the killing of fish in the Bay. The total number of fish killed was 32,658, with a total weight of 18,822 pounds. This resulted in an average of 1.36 pounds of fish per pound of explosive, a value much higher than recorded since 1958 (see Section 2.4.1).

It should be pointed out that the Patuxent River and Chesapeake Bay are utilized heavily by sports and commercial fishermen. They have been sources of complaints when an occasional heavy kill occurred. Complaints have also been received from residents on the river when dead fish drifted on shore. The latter situation is now prevented by the netting of dead fish after each test.

In regard to long range effects in the Patuxent River, the following statement was published by Tiller and Coker in 1955: "Examination of records of the commercial fishery of the Patuxent River for the period 1944-1953 show trends which follow generally the pattern of the Chesapeake Bay fishery. No decline has occurred which has not been evident in other areas supporting similar fisheries, and in which no explosive test programs have been conducted."

The available evidence, i.e., the statistical data and the results of a special study, indicate that the fish-kill by explosive testing in the Chesapeake Bay and the Patuxent River is negligible. In relative terms, the ratio of fish killed to the commercial catch is well below one percent.

In addition, it may be more significant that massive fish kills occur in the Chesapeake Bay estuary system as a result of natural causes and pollution. For example, 38 fish kills were recorded during 1971, including two herring mortalities on the Susquehanna River resulting from low water and a depletion of dissolved oxygen. The official estimate was over 1,250,000 fish (Holden, 1972). The total killed during the one year period was 16 million fish. The number of fish killed, even in extensive uncontrolled explosive test programs, is trivial compared to quantities of this magnitude.

However, when massive natural fish kills do occur in the vicinity of explosive test sites, it is essential that State authorities be notified promptly so that the cause can be determined. If this is not done, the possibility exists that uninformed observers will attribute the deaths to explosive testing.

5.2 CNO PROJECT D/S 580 - GULF OF MEXICO

CNO Project D/S 580 was a series of underwater explosion damage tests that are of special interest because the planned location was changed several times as a result of environmental considerations. The problem of major concern in this regard was the disposal of two target vessels, a destroyer and a cruiser.

TABLE 5.2
FISH MORTALITY DATA FROM NOLFB, SOLOMONS, MD

Year	Explosives Fired		Fish Killed			Average Mortality Relative to Explosions	
	Total Weight	No. of Shots	Edible	Non-Edible	Total		
	(lb)		(lb)	(lb)	(lb)	lb/shot	lb/lb
1958	19,000	44	613	7,107	7,720	175	.406
1959	9,000	70	247	4,003	4,250	60.7	.472
1960	22,000	65	807	14,553	15,360	236	.698
1961	12,000	195	312	6,218	6,520	33.4	.543
1962	14,000	45	561	2,069	2,630	58.4	.188
1963	13,000	42	291	1,529	1,820	43.3	.140
1964	16,000	82	290	5,070	5,360	65.4	.335
1965	36,000	272	640	11,470	12,110	44.5	.336
1966	34,000	53	556	2,304	2,860	54.0	.084
1967	35,000	178	275	995	1,230	6.91	.035
1968	42,000	209	1200	100	1,300	6.22	.031
1969	27,330	279	991	6,583	7,574	27.1	.277
1970	17,107	151	1036	1,064	2,100	13.9	.123
1971	5,928	143	575	1,001	1,576	11.0	.266
1972	18,505	70	170	337	507	7.24	.027

The test site selected in the early stages of planning was about 12 nautical miles southeast of Key West, Florida, and the tests were scheduled for January 1972. During July 1971, the planned location was changed to a position about 55 nautical miles west of Dry Tortugas as a result of a CNO stipulation that the target ship disposal be accomplished beyond 50 miles of the U. S. coast in water at least 6,000 feet deep. Although the water at the site was only a few hundred feet deep, the location was near the West Florida Escarpment and was within 14 nautical miles of a disposal area with a water depth in excess of 6,000 feet. The schedule was revised as a result of anticipated weather conditions in the new location. The CNO directive was evidently based on the policy established for the disposal of target ship hulls used in exercises at sea (Section 3.2.1).

However, during February 1972, the President of the Greater Key West Chamber of Commerce and the Mayor of Key West both recommended that the plan be modified and a new site be selected where the target ships could be sunk in relatively shallow water to provide artificial fishing reefs for the benefit of sport and commercial fishermen. On 28 March 1972, the Governor and Cabinet of the State of Florida, sitting as the Executive Board of the State Department of Natural Resources, passed a resolution formally requesting that the Navy sink the vessels at a site suitable for an artificial reef. These items are reproduced in Appendix B because of their general interest in regard to this concept.

An environment impact assessment was made by the Navy, showing that no adverse environmental effects were anticipated and that the reef would provide a haven for food and game fish where none existed. The net effect was therefore beneficial.

After considering other possible locations, it was decided to conduct the tests and scuttle the ships about 13 nautical miles east-southeast of Key West, off the American Shoals, at a position near the original site. The tests were conducted successfully and the target ships were sunk during May 1972. The locations were $24^{\circ} 27.8' N$ and $81^{\circ} 33.3' W$ for the destroyer and $24^{\circ} 28.8' N$ and $81^{\circ} 33.0' W$ for the cruiser.

The following agencies were apprised of the artificial reef proposal and no objections were made: The Department of Commerce, National Maritime Fisheries Service; The Department of Interior, Bureau of Sports, Fisheries and Wildlife; The Environmental Protection Agency; and the U. S. Army Corps of Engineers. A representative of the EPA inspected the two ships at the Key West Naval Station during April 1972 and determined that the cleanup procedures on the ships and tanks were reasonable and adequate. The U. S. Coast Guard had a patrol craft at the site each day an experiment was conducted in order to insure that vessels remained a safe distance from the targets and to monitor the effects the explosions had on the marine environment.

The damaged targets produced slicks that formed as a result of the bubbling of air to the surface. These bubbles transport fine particles and dissolved substances. However, no oil slicks were observed, and fish kill was observed on only one test, where about 50 red snappers were counted.

5.3 UNDERWATER EXPLOSIONS RESEARCH DIVISION, PORTSMOUTH, VIRGINIA

The Underwater Explosions Research Division (UERD) of the Naval Ship Research and Development Center is located at the Norfolk Naval Shipyard, Portsmouth, Virginia. The UERD conducts an average of 90 to 100 underwater explosion tests per year in the turning basin of the Shipyard, with 80 percent of the tests involving

charges weighing less than 20 pounds. The water is 40 feet deep and the charges are usually 24 feet deep. The authorized limit is 150 pounds.

As the site is near the shipyard, the Elizabeth River shipping channel, and a waterfront industrial area, there is no sport or commercial fishing and little aquatic life. Consequently, there is no concern about environmental effects on marine organisms.

The UERD also uses two test sites in the Chesapeake Bay; the deep channel utilized by NOLF (see Section 5.1) and Old Plantation Flats, northwest of the town of Cape Charles, Virginia. The tests in the Bay usually involve large charges, with weights ranging up to 15,000 pounds. The average rate is less than one test program per year.

NSRDC informs local, state, and federal authorities of planned experiments in the Chesapeake Bay and invites them to attend or send a representative. The list of those notified includes (Nichols, 1970):

- A. Senators (federal),
- B. Applicable member of House of Representatives,
- C. Regional Director, Bureau of Commercial Fisheries and Wildlife,
- D. Director, Bureau of Commercial Fisheries,
- E. Virginia Marine Resources Commission (Virginia waters only),
- F. Virginia Institute of Marine Science (Virginia waters only),
- G. Maryland Department of Chesapeake Bay Affairs (Maryland waters only),
- H. Chesapeake Biological Laboratory (Maryland waters only), and
- I. Maryland Marine Police (Maryland waters only).

Furthermore, the District Office of the U. S. Army Corps of Engineers and U. S. Coast Guard are notified, and the Coast Guard will subsequently issue a "Notice to Mariners" describing the experiments.

In general, the same procedures are followed as those employed by NOL, i.e., tests are not scheduled during the winter months, a fish finder is used to locate schools of fish in the firing area, the tests are delayed until the fish disperse, and dead fish are removed from the water. The test sites are far enough from shore to preclude effects on beaches or residential areas.

5.4 WEST COAST SHOCK FACILITY

The West Coast Shock Facility is located at the San Francisco Naval Shipyard at Hunter's Point. The underwater explosion tests conducted at this location are similar to those done at Norfolk Naval Shipyard and include charges weighing up to 60 pounds.

Tests are made against the Large Floating Shock Platform (LFSP) in a slip, and the policy is to sweep out the slip with nets before firing a charge. California State Fish and Game personnel are invited to witness all of the tests.

When operations are conducted off the end of the slip with 300-pound charges, sonar is used on a small boat to check for the presence of fish and the tests are delayed if schools of fish are present.

5.5 PANAMA CITY, FLORIDA

Various underwater explosion test programs have been conducted near the Naval Coastal Systems Laboratory at Panama City, Florida, in the waters of St. Andrew Bay and the Gulf of Mexico. The bottom of the Gulf is smooth and consists of hard sand, with a very gradual slope. The depth is 100 feet at a distance of about 12 nautical miles from shore. The water is clear enough for underwater photography.

As the tourist season extends from Memorial Day to Labor Day, explosive testing must usually be scheduled before or after these dates. During 1969, the Naval Ordnance Laboratory was permitted to fire in the Gulf during September and October after approval was given by the local Chamber of Commerce. However, it is now necessary for the Coastal Systems Laboratory to obtain clearance from the Florida Department of Natural Resources before scheduling a program.

The Waterways Experiment Station in Vicksburg, Mississippi, had planned an explosion test series in the Gulf during May 1971, but this was postponed for a review of possible environmental hazards. Permission was granted to conduct the tests during April 1972.

June is the best month for operations in the Gulf near Panama City. In the time period when explosion tests are permissible, May is probably the best month, followed by April, September, and October (Tolbert and Austin, 1959). This assessment is based on the number of days that small boats can operate, which is a result of a combination of meteorological and oceanographic factors.

5.6 MONO LAKE, CALIFORNIA

Mono Lake, California, has been used several times for multi-ton underwater explosion test programs because of its remote location, its accessibility, and the absence of fish and most wildlife. Because of the high salinity of the water, only brine shrimp can survive in the lake. These are seined, quick frozen, and marketed as fish food. In addition, there are several gull rookeries on the islands in the lake.

The most recent test program in Mono Lake was conducted by the Naval Ordnance Laboratory during 1969. Permission was granted by the California Fish and Game Commission on the condition that all possible care be taken to avoid disturbing the shrimp beds or the gull rookeries. In addition, a representative of the Commission was notified prior to each test so that he could witness each firing (Pittman, 1971).

During the test program, the rookeries were not affected, but large numbers of shrimp were killed. Complaints from the harvesters indicated that the quality of the product was degraded by large quantities of bottom scum and dead shrimp. However, ten days after the last shot, the harvesting company stated that the catch was back to normal except in the area where the firings had occurred. In this area, the shrimp concentration had increased. The explanation given was that the explosions had disturbed the bottom and sent large numbers of the eggs to the surface. The warmer water caused earlier hatching, thus increasing the concentration of shrimp.

This result, and the formation of artificial fishing reefs, provide examples of possible beneficial effects of explosion testing.

VI

RECOMMENDATIONS

6.1 PROPOSED CHECK LIST FOR AN ENVIRONMENTAL ASSESSMENT

The Geological Survey (Leopold, et al, 1971) has developed a matrix to be used as an aid in the preparation of Environmental Impact Statements. The matrix serves the purpose of insuring that all relevant items are considered and it also provides a means of evaluating the magnitude and importance of each proposed action.

As a less elaborate approach is adequate for underwater explosion testing, a simple check list has been prepared for the preparation of a complete Environmental Assessment or Impact Statement. The magnitude of most effects can be estimated from material in this report, but the importance of these will vary with the location of the site. However, it is expected that a site will be selected on the expectation of minimal environmental effects.

The following is the proposed Environmental Impact Check List.

ENVIRONMENTAL IMPACT CHECK LIST

A. Existing Characteristics of the Environment (Test Site)

Water - Salinity
Temperature
Currents
Sea State
Pollutants

Seabed - Depth
Composition
Slope

Atmosphere - Composition (Pollutants)
Wind Direction and Speed

Sea Life - Fish
Benthic Life
Sea Mammals
Plants

Recreational Activities - Boating
Fishing
Swimming
Beaches

Commercial Activities - Shipping
Fishing
Oil or Gas Wells

B. Effects on the Environment

Physical Effects (Magnitude and Duration)

Atmosphere - Noise
Smoke Cloud
Gases

Water - Heating
Solid Products
Gaseous Products

Beach - Deposit of Solid Products
Deposit of Bottom Material

Seabed - Cratering
Sediment Clouds
Turbidity Currents
Mud Slides

Biological Effects - Fish
Benthic Life
Sea Mammals
Plants

Dumping - Experimental Debris
Trash
Garbage
Targets
Explosives
Oil

C. Alternatives

Other Sites
Saline Lake
Quarry
Pond
Lake on Military Reservation
Beach on Military Reservation
Polluted Water
Tank

6.2 GENERAL COMMENTS

6.2.1 Recommended Research

Data are limited on all of the long-range environmental effects of underwater explosions, and such data should be acquired where possible. One feasible approach

is to sample the bottom and the water in locations where testing has continued over a period of years. These samples may be compared with samples acquired in similar nearby regions where no testing has occurred. The populations of marine organisms can also be compared in these areas. It would also be of interest to determine the geographic extent of the measurable effects of continued testing at a site.

Knowledge of the physical effects of bottom explosions is also relatively limited. This includes such effects as cratering in different soils in deep water, the displacement of bottom material, and the formation of sediment clouds and turbidity currents.

The highest priority, however, should be given to studies of the effects of explosions on marine life. This effort can be divided into two major problem areas; the biological effects on different species and methods of dispersing fish from an explosion test site.

The study of biological effects requires the placement of cages of various specimens of fish and benthic organisms at selected positions in the water and the recording of accurate shock wave pressure-time histories at each location. A sufficient number of specimens and tests is required to obtain meaningful statistical results. In addition, caged specimens should be placed in a natural environment as controls.

Even with an improved understanding of effects on biota, however, a requirement to minimize harm to marine life will always exist. It would therefore be highly desirable to develop a simple means of dispersing fish from an explosion test site prior to the firing of each shot.

The following methods have been suggested for attracting fish or driving them away; either approach is possible during a test program, but the use of certain dispersing equipment in the vicinity of the explosive or experimental gages may be unsafe or may interfere with the recording equipment.

Attraction

Radio Broadcasts (Wyatt, J. L., 1965)

Pulsed Electric Currents (Elliott, 1970; Crowther, 1969; Patten and Gillaspie, 1966)

Underwater Sound (Maniwa, 1970)

Underwater Structures (Roedel, 1971)

Lights (Roedel, 1971)

Dispersion or Barrier

Pulsed Electric Currents (Elliott, 1970; Crowther, 1969; Patten and Gillaspie, 1966)

Air Bubble Curtain (Kupfer and Gordon, 1966)

Radio Broadcasts (Washington Post, 1972)

Nets (Section 5.4)

Chemicals (Wisby, 1952)

6.2.2 Recommended Procedures for the Conduct of a Test

The following are recommended in addition to the normal administrative procedures required prior to the conduct of explosion tests at sea:

- A. Select a site compatible with the objectives of the test, but where possible undesirable effects on the environment are minimized. Select a site remote from public view, if possible.
- B. Estimate the magnitudes of all environmental effects. (Prepare an Environmental Assessment.)
- C. Discuss the plans informally in advance with local Naval personnel, Chambers of Commerce, and State and local officials in order to establish good working relationships and to anticipate possible objections or complaints. It is seldom possible for an outsider to judge the reaction of local residents to a proposed test.
- D. Invite State and local Fish and Game personnel to observe the tests and inspect the area before and after each explosion.
- E. Utilize methods to detect and disperse fish at the test site, and postpone firing if schools of fish remain in the vicinity.
- F. Scoop up all dead fish.
- G. Dump no trash, garbage, or debris of any kind.

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APPENDIX A

MEMORANDUM OF LAW ON AUTHORITY OF THE NAVY WITH RESPECT TO ITS USE OF
THE MARYLAND PART OF CHESAPEAKE BAY FOR TESTS AND TRAINING INVOLVING
UNDERWATER EXPLOSIONS *

January 2, 1970

I. Question Presented

1. Concern over the oyster population of Chesapeake Bay and the possible threat posed to it by underwater explosions conducted by the Navy in Chesapeake Bay resulted in an inquiry from the State of Maryland concerning the authority of the Navy to conduct these explosions. For purposes of this memorandum, this question is presented: Does the Navy have authority to conduct gunnery training and ordnance testing involving underwater explosions in the Maryland part of Chesapeake Bay?

II. Legal Authorities and Discussion

A. Constitutional Authority of the United States to Conduct Gunnery Training and Ordnance Testing Involving Underwater Explosions in the Maryland Part of Chesapeake Bay.

2. Constitutional authority for gunnery training and ordnance testing involving underwater explosions in the Maryland part of Chesapeake Bay exists by virtue of the war powers of the United States. Under the Constitution the United States has a right in and power of regulation and control of navigable waters for purposes of national defense, as well as for purposes of commerce and navigation. This right and power was recognized by the Supreme Court in Ashwander v. Tennessee Valley Authority (297 U.S. 288 (1936)). Addressing itself to the question of whether constitutional authority existed for the construction of Wilson Dam, the Court concluded that such authority existed by virtue of the war powers of the United States as well as by virtue of the commerce powers. The dam was constructed for the purposes of national defense and the improvement of navigation "in the exercise of the constitutional functions of the Federal government." (297 U.S. at 330.) The Court took judicial notice of the international situation existing at the time that the act authorizing the construction of the dam was passed by Congress, observing that "it cannot be successfully disputed that the Wilson Dam and its auxiliary plants, including the hydro-electric power plant, are, and were intended to be, adapted for the purposes of national defense." (297 U.S. at 327). In summary, from Ashwander it may be concluded that the United States has, under the war powers of the Constitution, a right in and power of regulation and control of navigable waters for purposes of national defense; furthermore, this right and power exists in peacetime as well as in time of war, for the power to wage war embraces the power to prepare for it. (See Constitution of the United States of America--Analysis & Interpretation 346 (1964 ed.).)

* Prepared at the request of the Chief of Naval Operations. Submitted as enclosure (1) to Judge Advocate General ltr JAG:131.6 JHS:skr Ser 34 to CNO, dated 5 January 1970.

3. Although Ashwander does not specify the degree of control of and activity in and on the navigable waters by the United States which the war powers authorize, its holding that Congress may, for the purposes of national defense, authorize the permanent impounding of water in a navigable stream for use in the production of electric power (in peacetime) argues that the degree of control of and activity in and on the navigable waters which the war powers authorize is broad. It may reasonably be construed as including the reasonable use of navigable waters, e.g., Chesapeake Bay, for tests and training involving underwater explosions, such training and testing being directly related to preparing for the defense of the nation.

B. Effect of the Submerged Lands Act on the Authority of the United States to Conduct Gunnery Training and Ordnance Testing Involving Underwater Explosions in the Maryland Part of Chesapeake Bay.

4. By virtue of the Submerged Lands Act of 1953, the United States has quit-claimed to the several states all right, title, and interest, "if any it has," to the lands beneath and natural resources within their boundaries. (43 USC 1311; People v. Hecher, 4 Cal. Rptr. 334 (Cal. App. 1960).) Specific provision is made in the Submerged Lands Act, however, that paramount to but exclusive of the states' proprietary rights of ownership, management, leasing, use, and development are the United States' "navigational servitude and rights in and powers of regulation and control" of the lands beneath and waters of navigable waters "for the constitutional purposes of commerce, navigation, national defense, and international affairs." (43 USC 1314.) Thus Congress, by virtue of the Submerged Lands Act, has in no way limited the United States' right in and power of regulation and control of navigable waters for the purposes of national defense; rather, it has specifically retained such right and power to the fullest extent provided for in the Constitution.

C. Statutory Authority for Navy Tests and Training Involving Underwater Explosions in the Maryland Part of Chesapeake Bay.

5. By virtue of section 5012, title 10, United States Code, the Navy is authorized to "develop aircraft, weapons, tactics, technique, organization, and equipment of naval combat and service elements." (10 USC 5012(c).) Implicit in this authorization is the authority to conduct gunnery training and ordnance testing involving underwater explosions, for such training and testing are clearly necessary in order to develop weapons, tactics, technique, and equipment of naval combat. Such training and testing are, of course, conducted with funds appropriated by Congress, which funds, when appropriated for research, development, test, and evaluation, are appropriated pursuant to authorization legislation. (See e.g., "Legal Basis for 1969 Navy Budget Estimates by Appropriation;" see also sec. 201, Pub. Law 90-500, 82 Stat. 849, as amended.)

6. Gunnery training and ordnance testing involving underwater explosions are expressly contemplated in section 3, title 33, United States Code, which provides, inter alia, that:

"In the interest of the national defense, and for the better protection of life and property . . . the Secretary of the Army is authorized and empowered to prescribe such regulations as he may deem best for the use and navigation of any portion or area of the navigable waters of the

United States . . . endangered or likely to be endangered by Artillery fire in target practice or otherwise, or by the proving operations . . . at any Government ordnance proving ground"

Although this provision does not confer authority upon the Navy to conduct gunnery training and ordnance testing involving underwater explosions, nor does it confer such authority upon the Secretary of the Army which authority may be delegated to the Navy, its clear import is that authority to conduct gunnery training and ordnance testing involving underwater explosions does exist. Pursuant to the authority conferred by it upon the Secretary of the Army detailed danger zone regulations have been promulgated which, inter alia, include areas of Chesapeake Bay used by the Navy for gunnery training and ordnance testing involving underwater explosions. (33 CFR 204.32, .36, .42, .46, .50, .51A.)

D. Implication of Maryland's Consent to Installation of a Calibration Range in the Mouth of the Potomac River.

7. Article I, section 8, clause 17 of the U. S. Constitution provides, inter alia, that Congress "shall have power to . . . exercise like authority [exclusive legislation in all cases whatsoever] over all places purchased by the consent of the legislature of the state in which the same shall be, for the erection of forts, magazines, arsenals, dock yards, and other needful buildings." This provision does not require state consent in order for the Federal Government to make a purchase; rather, it requires state consent in order for Congress to exercise exclusive legislative authority over an area purchased. (Paul v. United States, 371 U.S. 245 (1963).)

8. Article 96 of the Annotated Code of Maryland (1957) contains numerous provisions wherein the state of Maryland has consented to federal purchases. Among them is a provision whereby the state consents to the installation of a calibration range in the mouth of the Potomac River. (Sec 40.) As the foregoing indicates, this provision exists to confer upon Congress exclusive legislative authority over the area of the calibration range, not to authorize the purchase of land for the range, nor to authorize the installation of the range itself. It in no way indicates that Maryland's consent is necessary in order for the Navy to conduct underwater explosions in the Maryland part of Chesapeake Bay. In point of fact, consent is unnecessary, for the explosions are conducted by the Navy pursuant to statutory authorization, which authorization is pursuant to the war powers of the United States.

E. Effect of Maryland Statute Prohibiting Underwater Explosions.

9. Article 66C, section 247 of the Annotated Code of Maryland (1957) prohibits placing, throwing, or using explosives in Maryland waters except for bona fide engineering, milling, or mining purposes. This provision does not bar the Navy from conducting tests and training involving underwater explosions in the Maryland part of Chesapeake Bay. Under the Supremacy Clause of the Constitution, the United States, in the exercise of its constitutional functions, is not subject to the police power of the several states. (Ohio v. Thomas, 173 U.S. 276, 283 (1899).)

F. Limitations on Authority of Navy to Conduct Gunnery Training and Ordnance Testing Involving Underwater Explosions in the Maryland Part of Chesapeake Bay.

10. No provision specifically limits the authority conferred upon the Navy to conduct gunnery training and ordnance testing involving underwater explosions. However, section 3, title 33, United States Code, places the following limitation upon the authority of the Secretary of the Army to prescribe danger zone regulations:

"(T)he authority conferred shall be so exercised as not unreasonably to interfere with or restrict the food fishing industry, and the regulations prescribed in pursuance hereof shall provide for the use of such waters by food fishermen operating under permits granted by the Department of the Army."

11. This provision is in accord with the declaration of policy set forth in section 742(a), title 16, United States Code, which states, inter alia, that:

"The Congress declares that the fish, shellfish, and wildlife resources of the Nation make a material contribution to our national economy and food supply, as well as a material contribution to the health, recreation, and well-being of our citizens . . . that the fishing industries strengthen the defense of the United States . . . that the training and sport afforded by fish and wildlife resources strengthen the national defense by contributing to the general health and physical fitness of millions of citizens. . . . The Congress further declares that the fishing industry, in its several branches, can prosper and thus fulfill its proper function in national life only if certain fundamental needs are satisfied by means that are consistent with the public interest and in accord with constitutional functions of governments. Among these are:

(1) Freedom of enterprise -- freedom to develop new areas, methods, products, and markets in accordance with sound economic principles as well as freedom from unreasonable administrative or legal restrictions that unreasonably conflict with or ignore economic needs."

12. Claims relating to loss of property rights by virtue of the danger zone regulations promulgated for Chesapeake Bay have been considered in at least two Court of Claims cases. (Jackson v. United States, 103 F. Supp 1019 (Ct. Cl. 1952); Todd v. United States, 292 F. 2d 841 (Ct. Cl. 1961).) In Todd v. United States, a congressional reference case involving claims for the value of fishing nets and equipment and property rights in certain fishing locations in Chesapeake Bay allegedly taken by the Secretary of War (without just compensation) by his declaration of danger zone regulations, the Court of Claims held that the claims, although barred by limitations, were legitimate. The particular regulations established restricted and prohibited areas for military purposes arising out of the activities of the Patuxent Naval Air Station. The regulations reduced the number of nets the plaintiffs could fish, limited the hours they could fish, and made their operation inherently dangerous by reason of the location of the nets within the gunnery range. By virtue of Maryland law, the plaintiffs had a property right in the fishing grounds. The court found that there had been an

actual taking of private property for public use without just compensation. The government "permanently deprived plaintiffs of property from which they earned their living and which they had the right to sell or devise. It had a value, and defendant is equitably, and but for the statute of limitations would legally be, required to pay for appropriating it." (292 F.2d at 845.)

13. According to the court, the Secretary's authority to issue regulations in the interest of national defense and protection of life and property on navigable waters was specifically restricted by section 3 of title 33 to such as would not unreasonably interfere with the food fishing industry. "Defendant's actions here were an unreasonable interference." (292 F.2d at 845-46.) Thus the court did not question the constitutional authority for the danger zone regulations, or for the activities necessitating the regulations. It appears to have recognized a federal right to regulate navigable waters for the purpose of national defense. It did conclude that the Secretary's authority to issue danger zone regulations was expressly restricted by Congress. Liability, it would seem, resulted because the Secretary acted beyond the scope of authority conferred upon him by Congress.

14. From the foregoing authorities it appears that the Navy, when conducting gunnery training and ordnance testing involving underwater explosions in the Maryland part of Chesapeake Bay, must not unreasonably interfere with or restrict the food fishing industry, its authority to train and test being no greater than the Secretary of the Army's authority to prescribe navigation regulations related to this training and testing. Where the Navy, in conducting gunnery training and ordnance testing involving underwater explosions in the Maryland part of Chesapeake Bay, unreasonably interferes with or restricts the food fishing industry, it may, as a consequence, subject the United States to liability for any property "taken".

15. The limits of "reasonableness" in this context are impossible to define. In the final analysis, the decision as to when and to what extent to conduct gunnery training and ordnance testing involving underwater explosions in the Maryland part of Chesapeake Bay is one of policy. Weighed against the needs of the Navy in preparing to meet its mission must be the adverse public reaction, the resulting acrimony, and the real damage to food fishing.

G. Possible Acquisition of Easement by Prescription.

16. In view of the extended period of time during which the armed forces have conducted underwater explosions in Chesapeake Bay, the United States may have acquired by prescription against the State of Maryland an easement in Chesapeake Bay for the continued conduct of these activities. Having concluded that these activities are authorized by the war powers of the Constitution, it is not necessary to discuss the question of a possible easement.

III. Conclusion.

17. From the foregoing, it is concluded that the Navy has authority to conduct gunnery training and ordnance testing involving underwater explosions in the Maryland part of Chesapeake Bay, such authority being limited only to the extent that training and testing involving underwater explosions which unreasonably interfere with or restrict the food fishing industry may subject the United States to liability for resulting damage.

APPENDIX B

CORRESPONDENCE RELATING TO DISPOSAL OF TARGET VESSELS
AS FISHING REEFS NEAR KEY WEST, FLORIDA

- Item 1 Letter from the Greater Key West Chamber of Commerce to Rear Admiral John H. Maurer, USN, of 22 February 1972.
- Item 2 Letter from the Mayor of Key West to Rear Admiral John H. Maurer, USN, of 23 February 1972.
- Item 3 Letter from the State of Florida Department of Natural Resources to Rear Admiral John H. Maurer, USN, of 28 March 1972, with enclosure.

The Greater Key West
CHAMBER OF COMMERCE

402 Wall Street, Old Mallory Square, Key West, Florida 33040

February 22, 1972

Rear Admiral John H. Maurer, USN
Commander Key West Force
Key West, Florida 33040

Dear Admiral Maurer:

As we both are aware, one of the outstanding attractions of Key West is sport fishing, and one of its sustaining industries is commercial fisheries. The economy of the City is therefore greatly dependent on our visitors and the basic income from our fishermen. Obviously only good fishing can keep this resource healthy.

The most lucrative areas for fishing are found around the many wrecks and sunken hulks of ships in the vicinity of Key West. These sunken ships provide a favorable environment for the development of large populations of some of the most popular fish. Unfortunately, the locations of many of the sunken hulks are either unknown or are too remotely located in relation to Key West to be available to the fishermen.

It has come to my attention that the U. S. Navy sometimes deliberately sinks obsolete or unusable ships in the deep waters of the ocean. A more practical disposition of these ships would appear to be to sink them in the vicinity of the Keys in water of from 250 to 400 feet of depth where they could be available to the public as ideal fishing spots. The locations could be chosen so that they could pose no hazard to navigation or damage to the ecology of the area.

Should you agree with the above, I would recommend that the matter be studied by the Navy and if feasible that consideration be given to disposing of one or two obsolete ship hulls in relatively shallow water near Key West.

Sincerely yours,

W. B. Hannum, Jr.
President

Mayor
Charles McCoy

City of
KEY WEST

Key West, Florida
Office of the
MAYOR

23 February 1972

Rear Admiral John H. Maurer
Commander Key West Force
Naval Station
Key West, Florida 33040

Dear Admiral Maurer:

I am aware of the efforts by the Greater Key West Chamber of Commerce to induce the Navy to help improve the fishing conditions of the Key West area by sinking obsolete ships in certain selected locations. Such action, if approved, should greatly enhance both the sport fishing and commercial fishing potentials of Key West.

Additionally, the fine relations which already exist between the Navy and the citizens of Key West would be further improved by an action of this type on the part of the Navy.

I heartily endorse the idea and wish to add my support to its early implementation.

Sincerely yours,

Charles McCoy
Mayor

STATE OF FLORIDA
DEPARTMENT OF NATURAL RESOURCES

Larson Building / Tallahassee 32304 / Telephone 224-7141

RANDOLPH HODGES
Executive Director

March 28, 1972

Admiral John Maurer
United States Navy
Key West, Florida

Dear Admiral Maurer:

Enclosed is a resolution that was adopted today by the Governor and Cabinet, sitting as the Executive Board of the Department of Natural Resources. This resolution requests the placing of the two cruisers near the American Shoals to be used as an artificial fishing reef.

Your cooperation is greatly appreciated and the staff of this Department and other state agencies involved stand ready to lend all possible assistance.

Sincerely,

Randolph Hodges
Executive Director

RH/ia

Enclosure

R E S O L U T I O N

WHEREAS, it has been brought to the attention of the Department of Natural Resources that the United States Navy proposes to dispose of two 900-foot cruisers by sinking them in 6,000 feet of water 75 miles west of Key West, Florida, in the Gulf of Mexico, on May 1, 1972, and

WHEREAS, several local salt water fishing organizations have previously expressed a desire for the State to install fishing reefs to improve fishing in Florida waters, and

WHEREAS, the State of Florida Department of Natural Resources is desirous of obtaining the said vessels to be used as an artificial reef along the natural reef line off American Shoals for the benefit of the fishermen of the State,

NOW, THEREFORE, BE IT RESOLVED, that the Governor and Cabinet, in a regularly scheduled meeting in Tallahassee, Florida, do formally request that the United States Navy remove all potential pollutants from the aforesaid vessels and that said vessels be sunk near the reef line off American Shoals in State waters at a site selected by the Department of Natural Resources, in cooperation with the Board of Trustees of the Internal Improvement Trust Fund and the Department of Pollution Control, as agreed to by the United States Navy.

DONE AND ADOPTED ON THIS THE 28th day of March A. D., 1972.

Reubin O'D. Askew
GOVERNOR AND CHAIRMAN

APPENDIX C

ALTERNATIVES TO TESTING AT SEA

Method	Advantages	Disadvantages
Saline Lake	Usually no Biota except brine shrimp No charge weight limitation	Corrosive effect of water No ship targets Depth limitation
Quarry or pond	No fish kill Water effects confined	Limited charge weight No ship targets Depth limitation
Laboratory tank	No environmental effects Sub-surface photography Low cost rate	No realistic targets Possible surface tension effect
Lake or beach on military reservation	No public complaints, except possibly for noise	No ship targets Depth limitation
Polluted water	No harmful effects on marine environment	Health hazard Possible effects on shore facilities

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Ornellas, et al, (1966) and Ornellas (1968) investigated the products of detonation of PETN ($C_5H_8N_4O_{12}$), TNT ($C_7H_5N_3O_6$), HMX ($C_4H_8N_8O_8$), NM (CH_3NO_2), and FEFO ($C_5H_6N_4F_2O_{10}$). As the latter two are not used in Navy programs, they will not be considered here. Ornellas analyzed the products of the explosives in a calorimeter and compared the results with calculations based on different theoretical approaches for confined and unconfined charges. The products are listed in Table 2.1A as given in his publications. It should be noted that the C-H-N-O compositions utilized were selected to provide a wide range of oxygen balance, therefore, the quantities of products listed represent the range of amounts to be expected from this type of explosive. In brief, an explosive such as TNT is oxygen-deficient and it forms relatively large amounts of carbon and hydrogen, while PETN, an oxygen-rich explosive, produces less hydrogen and no carbon.

The compositions of other C-H-N-O explosives were reported by Kamlet and Jacobs (1968). This publication and a paper by Kamlet and Ablard (1968) present discussions of the detonation properties and chemical products of explosives. It should be noted that some authors believe that nitric oxide is an explosion product, though a minor one.

Table 2.1B presents the same data as in Table 2.1A in terms of percentage by weight. This form might be more useful for quickly estimating the total amount of a particular substance deposited in the environment by a test with an explosive charge of a known weight.

It seems reasonable to assume that the products of an underwater explosion will be the same as those of a confined charge and that an unconfined charge is representative of a surface burst.* It is not clear where the transition will actually take place; however, it seems likely that explosives at a depth of two or more charge radii will behave like confined charges.

To properly evaluate the ultimate disposition of explosion products in the marine environment it is necessary to treat them in at least three categories: gases, insoluble solids (particulates), and soluble solids. The gases, of course, are soluble in water; but most of the gaseous products will escape to the atmosphere unless an explosion is exceptionally deep. Initially, the products are contained in a large spherical bubble that pulsates and migrates toward the surface (see Section 2.3.3.2); and the gaseous composition of the bubble is of particular interest for evaluating the rate of solution.

The gases formed by the three explosives considered thus far are listed in terms of percentage by volume in Table 2.2. These values may be readily converted to partial pressure, as in Table 2.3 of Section 2.3.2.1. Water vapor and hydrogen cyanide are treated as gases here, although they partially or completely condense to the liquid state at some later time.

It may be noted that the majority of the products of these explosives are found in the natural environment and are harmless to man and to marine life. This is not necessarily true for carbon monoxide (CO) and hydrogen cyanide (HCN). However, both are rapidly diluted to low levels of concentration, as will be shown in Sections 2.3.3.1 and 2.3.3.2.

* In this report, an explosion is considered to be a surface burst if at least half the charge is exposed to the air.

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13. ABSTRACT

The environmental effects of conventional underwater explosions are described and quantitative estimates provided where possible. These effects include noise, the deposit of chemical products in the sea and atmosphere, cratering and other bottom disturbances, and the killing of fish and other sea life. The long term effects on the environment are minimal. Nevertheless, knowledge of these is needed to avoid unnecessary harm and to fulfill legal and administrative requirements, including the preparation of Environmental Impact Statements. Also, explosion effects knowledge can be utilized during the planning stages to avert unnecessary delays or interference with essential military test programs.

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